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WADC TECHNICAL REPORT 52-288

DESIGN EQUATIONS FOR THE INTERWARMER INDUCTION AIR HEATING SYSTEM FOR RECIPROCATING AIRCRAFT ENGINES

EDWARD C. THEISS
WEAPONS SYSTEMS DIVISION

NOVEMBER 1952

WRIGHT AIR DEVELOPMENT CENTER

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DESIGN EQUATIONS FOR THE INTERWARMER INDUCTION AIR HEATING SYSTEM FOR RECIPROCATING AIRCRAFT ENGINES

Edward C. Theiss
Weapons Systems Division

November 1952

SEO No. 560-80

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

Mr. E. C. Theiss of the Aircraft Special Projects Branch, Weapons Systems Division, Deputy for Operations, WADC, was project engineer on the development of the Interwarmer Induction Air Heating System. This report was prepared in order to finalize the development of the Interwarmer System and to provide equations for design and application of this system to any type reciprocating engine installation. The methods used are also applicable to development of design equations for any flow heat transfer process having similar limiting conditions. This project was accomplished as one phase of project SEO 560-80, "Aircraft and Missiles USAF - Winterization of."

Those organizations which cooperated in the development of the Interwarmer System and this study are the Power Plant Laboratory, Directorate of Laboratories, and the Directorate of Flight and All-Weather Testing.

ABSTRACT

The Interwarmer Induction Air Heating System is a development of the exhaust manifold and accessory section types. It ducts hot air from around the exhaust manifold over heat exchanger tubes to transmit heat to the induction air. The hot air flow is controlled by a valve in the duct on the inlet side of the heat exchanger, and induced and regulated by the venturi action of the airstream on a rearwardly facing flap on the outlet side of the duct.

An installation was made in a B-29 aircraft having R-3350-57 engines, and instrumentation and testing was accomplished to define the temperature and flow conditions in the interwarmer system and in the contributing exhaust and induction systems. Due to uncontrollable circumstances, air and gas weight flow data of some systems were questionable. As an alternative, test stand flow data from a similar engine were blended with the flight temperature data and empirical equations developed.

The induction system energy balance reduced empirically to $(T_{5a}-T_a) = 62.2°R$ representing the total enthalpy change between outside air and carburetor top deck. The interwarmer system energy balance reduced to a summation of the total enthalpy gain over the exhaust manifold, $(T_{1h}-T_a) = 127.8°R$; loss to interwarmer inlet, $(T_{3h}-T_{2h}) = -21.6°R$; loss over interwarmer tubes, $(T_{4h}-T_{3h}) = -41.4°R$; and loss overboard, $(T_a-T_{4h}) = -66.6°R$; while that for the exhaust system reduce to $(T_{1g}-T_g) = -42°R$. From these equations the interwarmer air weight flow in terms of induction and exhaust gas weight flow becomes

$$W_h = 1.48\ W_a \text{ and } W_h = 1.375\ W_g.$$

From the above, it is found that the minimum area of the interwarmer duct is $A = .188\ W_h$, and the rate of heat transfer at the interwarmer and at the exhaust manifols is $q_i = 14.7\ W_a = 9.94\ W_h$ and $q_{em} = 48.2\ W_g = 30.7\ W_h$, respectively.

The above equations will provide an interwarmer system for a reciprocating engine capable of providing a carburetor air temperature of 0°F (-17.8°C) at -65°F (-53.8°C) which is sufficient to meet USAF requirements.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

Louis W. Tibbett, Lt Col. USAF

for VICTOR R. HAUGEN
Colonel, USAF
Chief, Weapons Systems Division
Deputy for Operations

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DESIGN EQUATIONS FOR THE INTERWARMER INDUCTION AIR HEATING SYSTEM

CHAPTER I - INTRODUCTION

The purpose of this report is to develop design equations for application of the Interwarmer Induction Air Heating System to any aircraft having a reciprocating engine installation.

The initial work to provide a satisfactory induction air heating system for turbo-supercharged engine aircraft was installation and test of an exhaust manifold type system on a B-17 and an accessory section type system on a B-24 during the fall of 1943 and winter of 1943-1944. The exhaust manifold system ducted heated air from around the exhaust manifold to the inlet of the induction system ahead of the supercharger as shown in Figure I.1. The accessory section system closed off the intercooler cooling air flow and opened a valve into the accessory section to allow circulation of the warm air over the intercooler tubes as shown in Figure I.2. A combination of the best features of these two systems lead to the original conception of the interwarmer induction air heating system presented in Figure I.3. The heat source of the exhaust manifold system was combined with the method of heating of the accessory section system. Hence, the interwarmer system ducts heated air from the exhaust manifold over the intercooler tubes. The tests and results of the exhaust manifold and accessory section systems and a discussion of the proposed interwarmer design are presented in Reference 1, Appendix.

As a result of a B-29 aircraft crash on 12 December 1946 at an outside air temperature of -47°F (-43.8°C), which was attributed to loss of power and engine malfunctioning caused by extreme low carburetor air temperatures, the WADC, then the AMC, was directed by letter from Chief, Research and Engineering Division, AC/AS-4, Headquarters USAF, dated 26 February 1947, subject "Engine Malfunctioning at Extremely Low Temperatures," to "provide such modifications to aircraft engine installations as is necessary to permit satisfactory engine operation throughout the temperature range of -65°F to 160°F (-53.8°C to 71.1°C) in accordance with existing policy." The Power Plant Laboratory analyzed all available past and current data and again confirmed the necessity and desirability of adequate carburetor heat as the best remedial action for alleviating loss of power and engine malfunctioning at extreme low temperatures. Action was immediately taken to obtain a satisfactory carburetor heat system for such aircraft as the B-29, F-47, and F-51. The author was assigned the project of developing the interwarmer system proposed in Reference 1 for the B-29 while other developments for these aircraft were accomplished under contract with industry. Two types of systems were installed on a B-29 and were tested at Ladd Air Force Base, Alaska, under supervision of the author, during 18 February to 16 March 1948 for possible application to B-29 aircraft. Engines 1 and 2 of B-29, Serial No 45-21698, were provided with an interwarmer system similar to that proposed in Reference 1 and described and evaluated in Reference 2. Engines No 3 and 4 were provided with a recirculating type system designed by Boeing Airplane Company which is described and evaluated in Reference 3. The recirculating system bled off

NOTE: Induction Air Heating System in Operation When Valves A and B are as Shown.

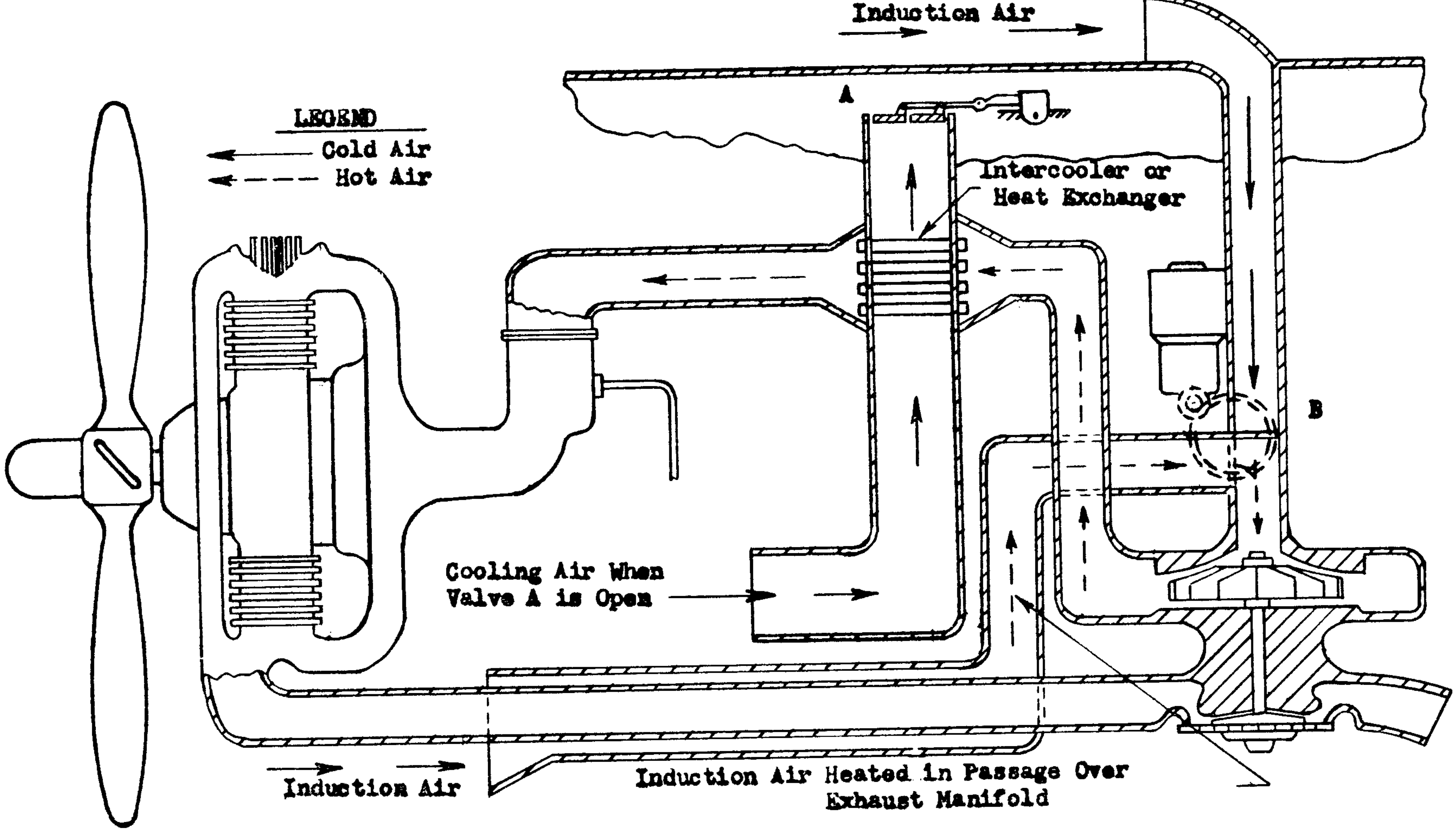


FIGURE I.1

EXHAUST MANIFOLD INDUCTION
AIR HEATING SYSTEM

NOTE: Induction Air Heating System in Operation When Valve is Positioned as Shown.

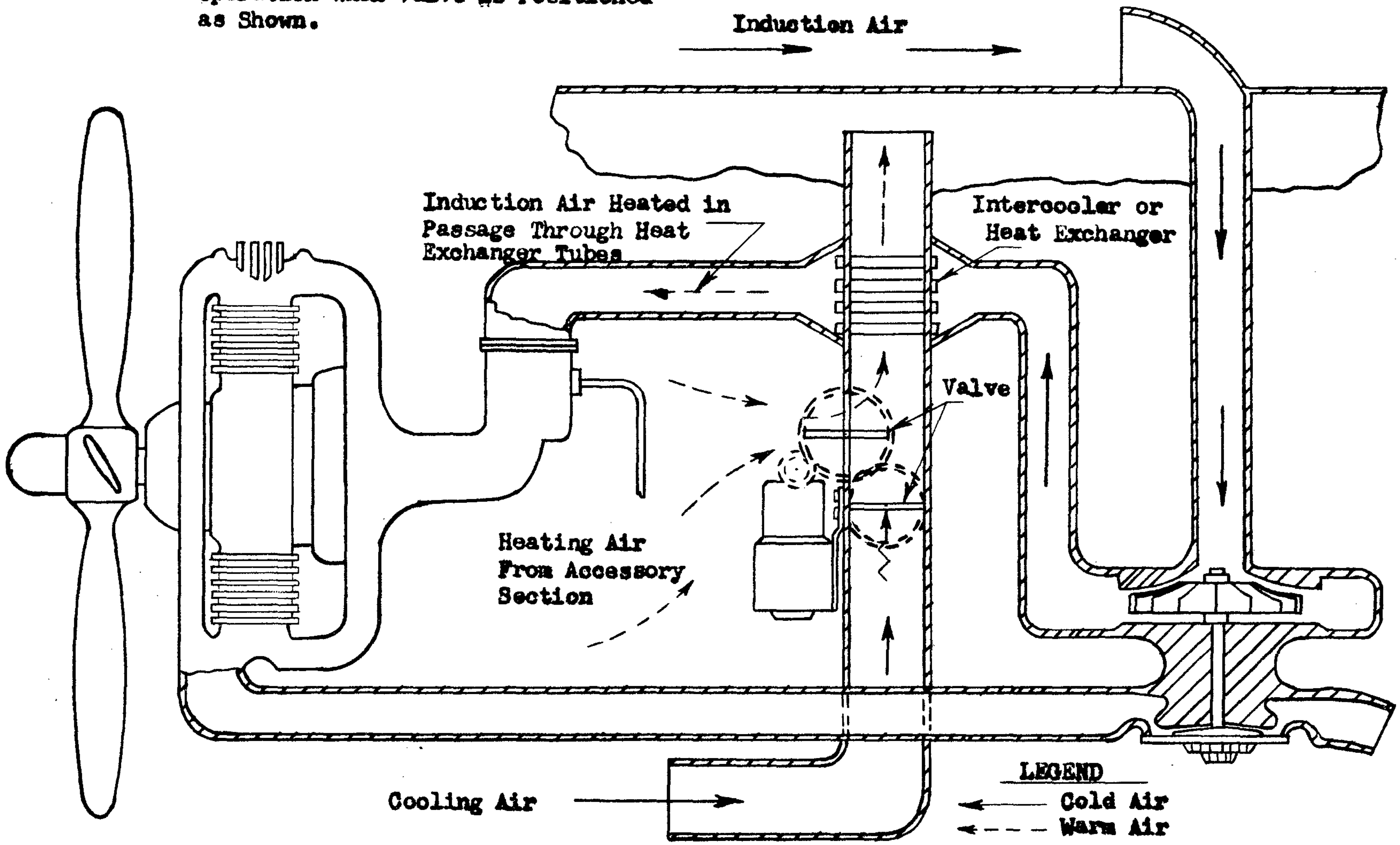


FIGURE I.2
ACCESSORY SECTION INDUCTION AIR HEATING SYSTEM

NOTE: Induction Air Heating System in Operation When Valve is in Position A. Temperature Controlled by Positioning Valve Between A and B as Required.

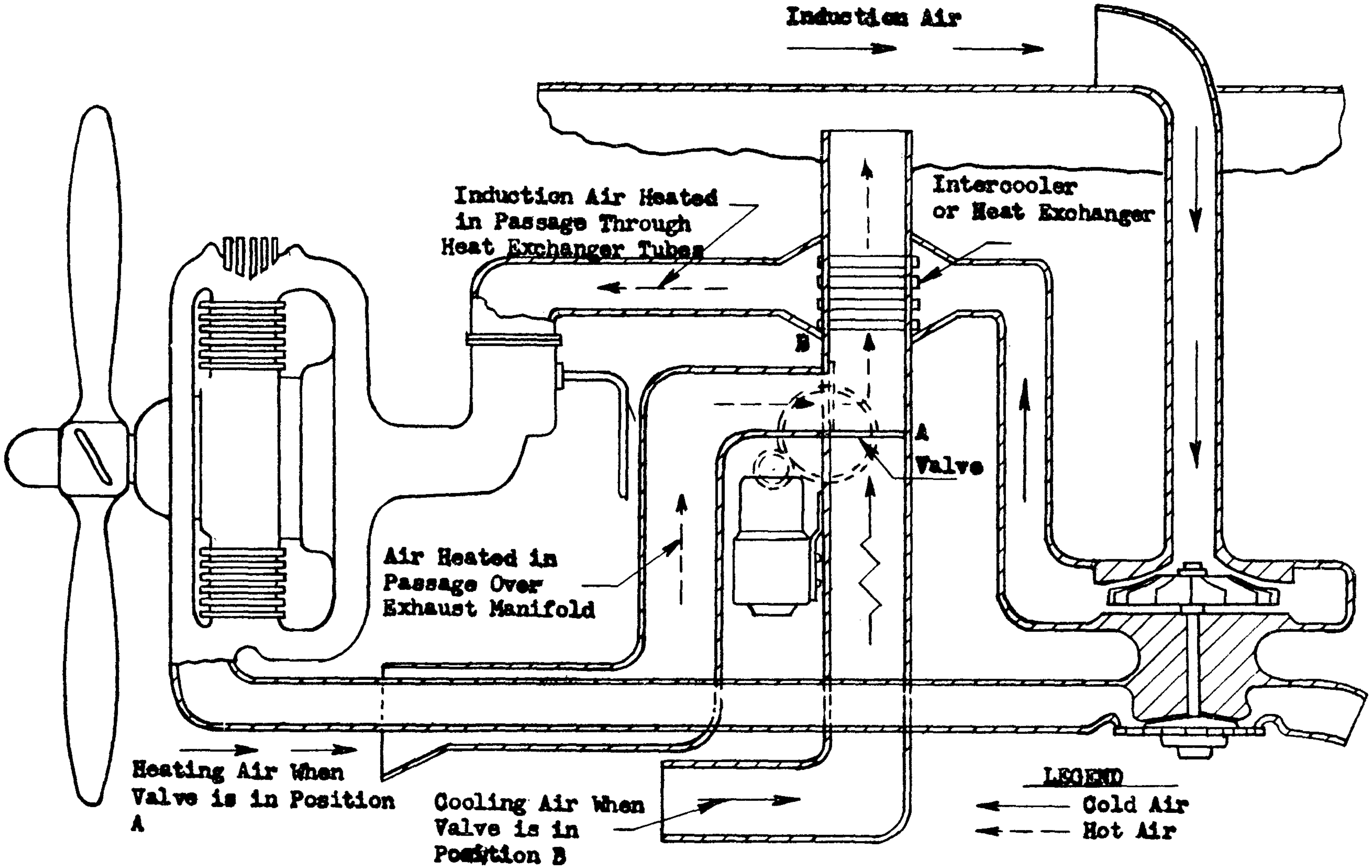


FIGURE I.3

ORIGINAL CONCEPTION OF THE INTERWARMER INDUCTION AIR HEATING SYSTEM air from the outlet side of the turbosupercharger and recirculated it back through the inlet in order to increase the induction air temperature. Since this system did not add to the development of the interwarmer system and proved inadequate, no further reference or discussion of this system will be made. Other developments which further refined the interwarmer system, but which have no effect on development of the design equations, are design and installation of fire valves in the inlet of the interwarmer system to prevent entry of flame from engine or exhaust system fires, and a balanced type heat control valve to be used in lieu of the cantilever valve. These refinements are described in detail in References 4 and 5. The fire valve has been made a production change to the kit and has been applied as a service change to aircraft having the system previously installed. The balanced type heat control valve has been held in the inactive status since the cantilever valve has performed satisfactorily and provided a sufficient carburetor air temperature rise.

Application for patent of an induction system comprising the air interwarmer and air intercooler was filed 20 May 1949. Patent 2,558,797, "Air Induction System for Turbosupercharged Aircraft Engines, Including Air Intercooler and Air Interwarmer," was issued 3 July 1951 to the author with license to manufacture or use granted to the United States Government.

CHAPTER II - INSTALLATION, INSTRUMENTATION, AND TEST PROCEDURES

Description of Installation

The final version of the interwarmer induction air heating system is the heating portion of "The Air Induction System" described in the aforementioned Patent No 2,558,797. This system, a refinement of that of Figure I.3, is shown schematically in Figure II.1. This system consists of an air induction system having a heat exchanger interposed preferably near the carburetor to minimize heat losses. In a turbosupercharged engine installation, this heat exchanger would be the intercooler, but in this system is given another function for which it is termed interwarmer. The inlet side of the heat exchanger is ducted to the atmosphere and to a source of warm air. A remotely controlled valve for simultaneously opening one duct and closing the other is actuated to control the admission of either cooling or heating air to the heat exchanger. The air outlet duct of the heat exchanger communicating with the atmosphere has an adjustable remotely controlled flap valve fitted in the discharge end. The valve extends rearwardly so that the slipstream will induce outward flow of air from the duct. The amount of opening of this latter valve determines the extent of cooling or heating. On turbosupercharged aircraft this latter valve would be the intercooler exit shutter.

As applied to the B-29, this system ducted hot air from the shroud above the supercharger on each side of the nacelle to a manifold and thence into the duct connecting the intercooler with the outside air. A valve which simultaneously opens the one duct and closes the other is located at this point. The cooling air portion of the system is the same as the production configuration and consists of a ram air duct connected to the intercooler and the intercooler exit shutter. A spring-loaded fire valve held open by an antimony-lead fuse with a melting point of about 412°F is located in each of the inlets of the interwarmer ducts to prevent entry of fire and excessively high exhaust gas temperatures. The entire system as applied to B-29 aircraft is shown in Figure II.2. As mentioned in the "Introduction" the interwarmer system has been installed on all engines of B-29, Serial No 45-21698. Control is the same for all engines and is accomplished by placing the heat valve in the hot or cold position by means of single pole double throw switches mounted at the left of the engineer's station as shown in Figure II.3. Selection of specific carburetor air temperatures is attained by opening the intercooler shutter so that the modified intercooler shutter indicator shown in Figure II.4 rests in the green range. The greater the CAT rise desired the further the indicator needle is moved into the green range. The end of the green range represents the greatest heat rise available with optimum performance of the aircraft. The major difference between installations exists in the type of heat control valve employed and in slight variation in shape of ducting. Engines 1 and 2 have balanced type heat control valves, while Engines 3 and 4 have the cantilever type valves. Since the type of valve does not affect development of the design equations it will suffice to refer to References 2 and 4 for detailed description of these valves. Engines 2 and 3 provided

NOTE: Induction Air Heating System in Operation When Valve A and Valve B are as Shown. Induction Air Temperature Rise is Directly Proportional to the Opening of Valve A. Hot Air Flow Over Interwarmer Tubes is Induced by Venturi Effect of Airflow Over Valve A When Open.

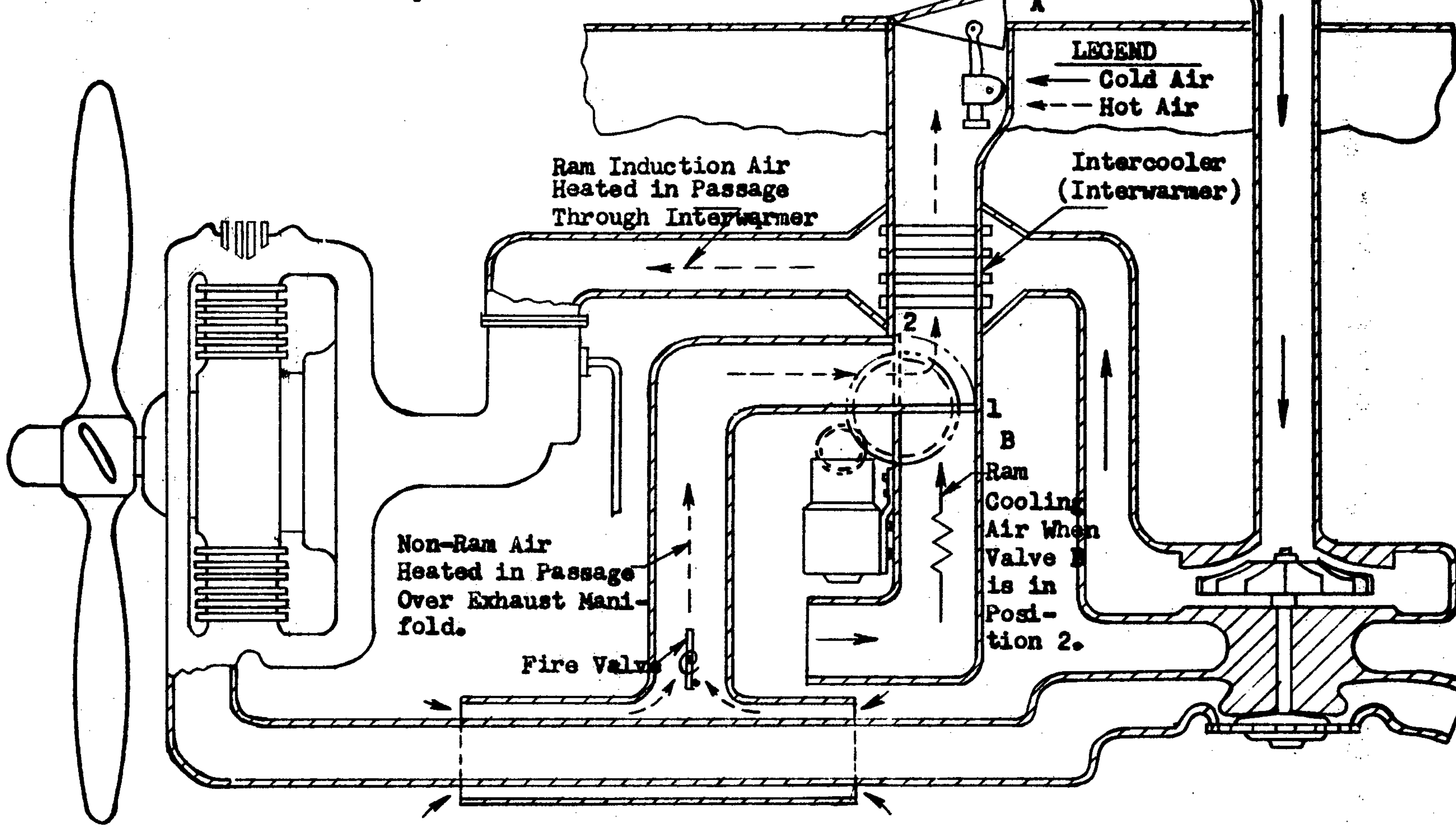


FIGURE II.1

FINAL ARRANGEMENT OF THE INTERWARMER
INDUCTION AIR HEATING SYSTEM

The Interwarmer System is in Operation When Valves A and B are as Shown. The Induction Air Temperature can be Maintained at That Desired by Opening or Closing Valve A. The Induction Air Temperature Rise is Directly Proportional to the Opening of Valve A. Hot Air Flow Over Interwarmer Tubes Induced by Venturi Effect of Airflow Over Valve A.

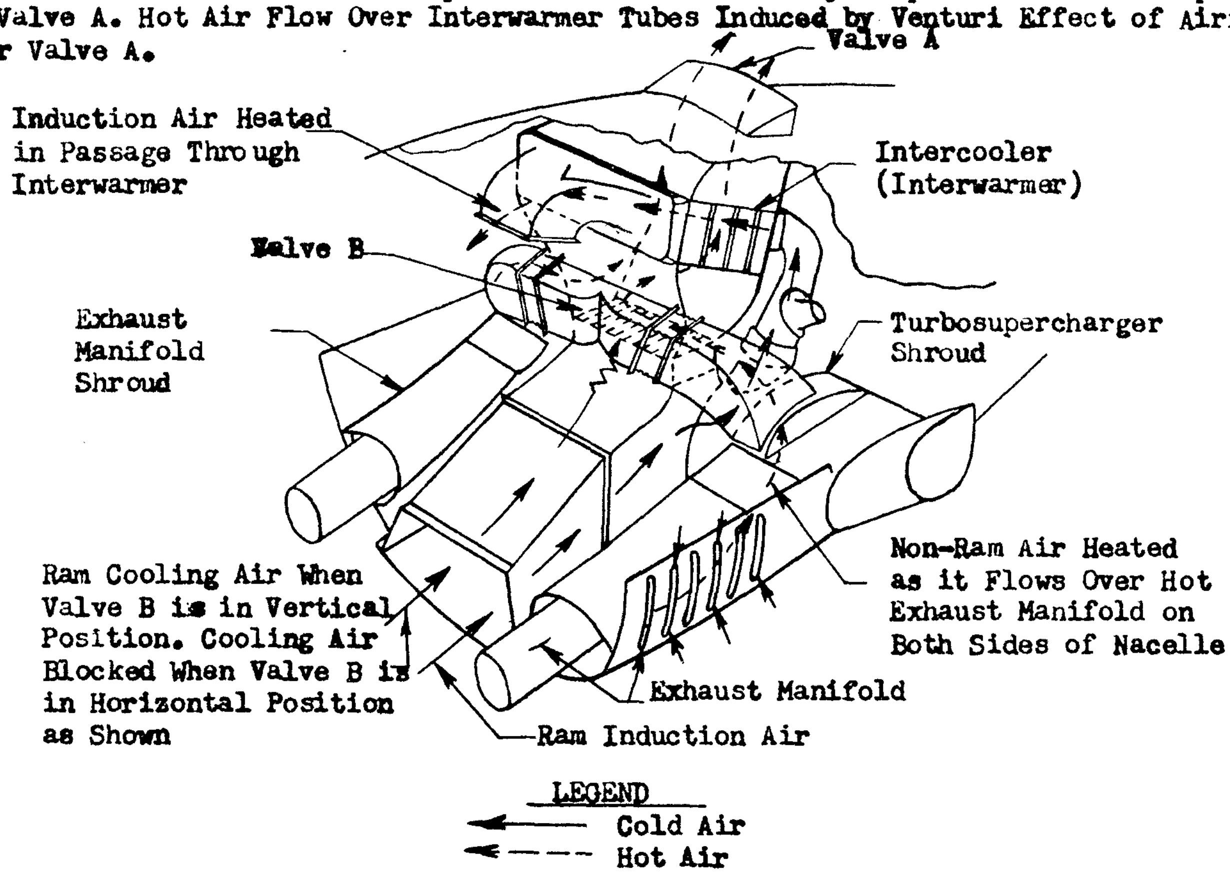


FIGURE II.2

INTERWARMER INDUCTION AIR HEATING SYSTEM AS APPLIED TO B-29 AIRCRAFT

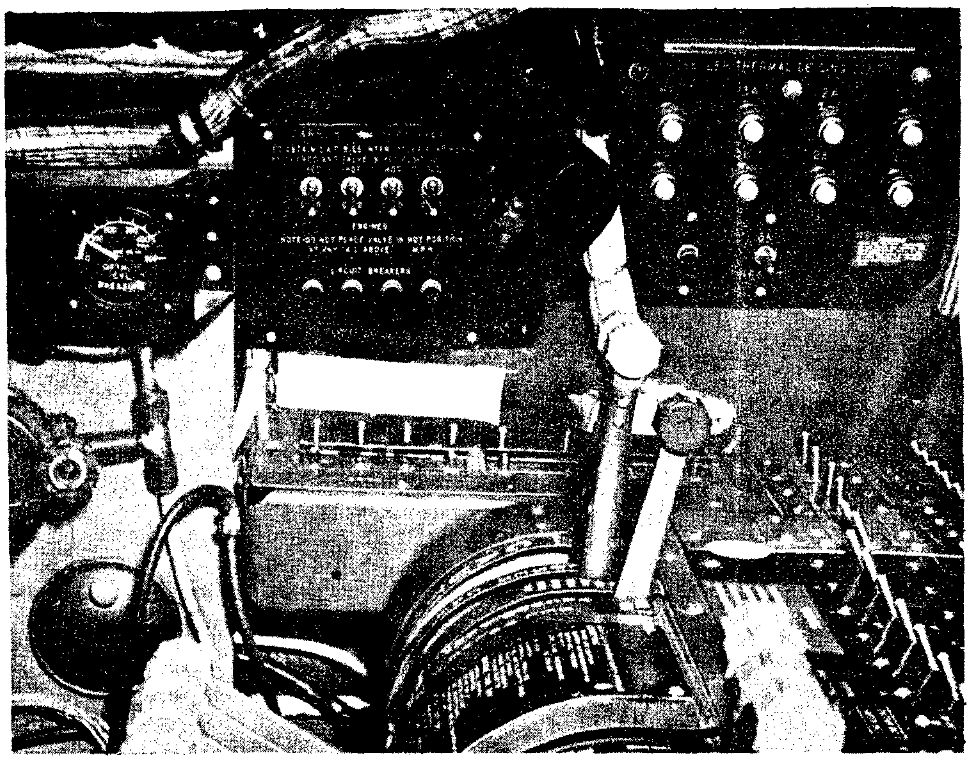


FIGURE II.3

HEAT VALVE SWITCH PANEL

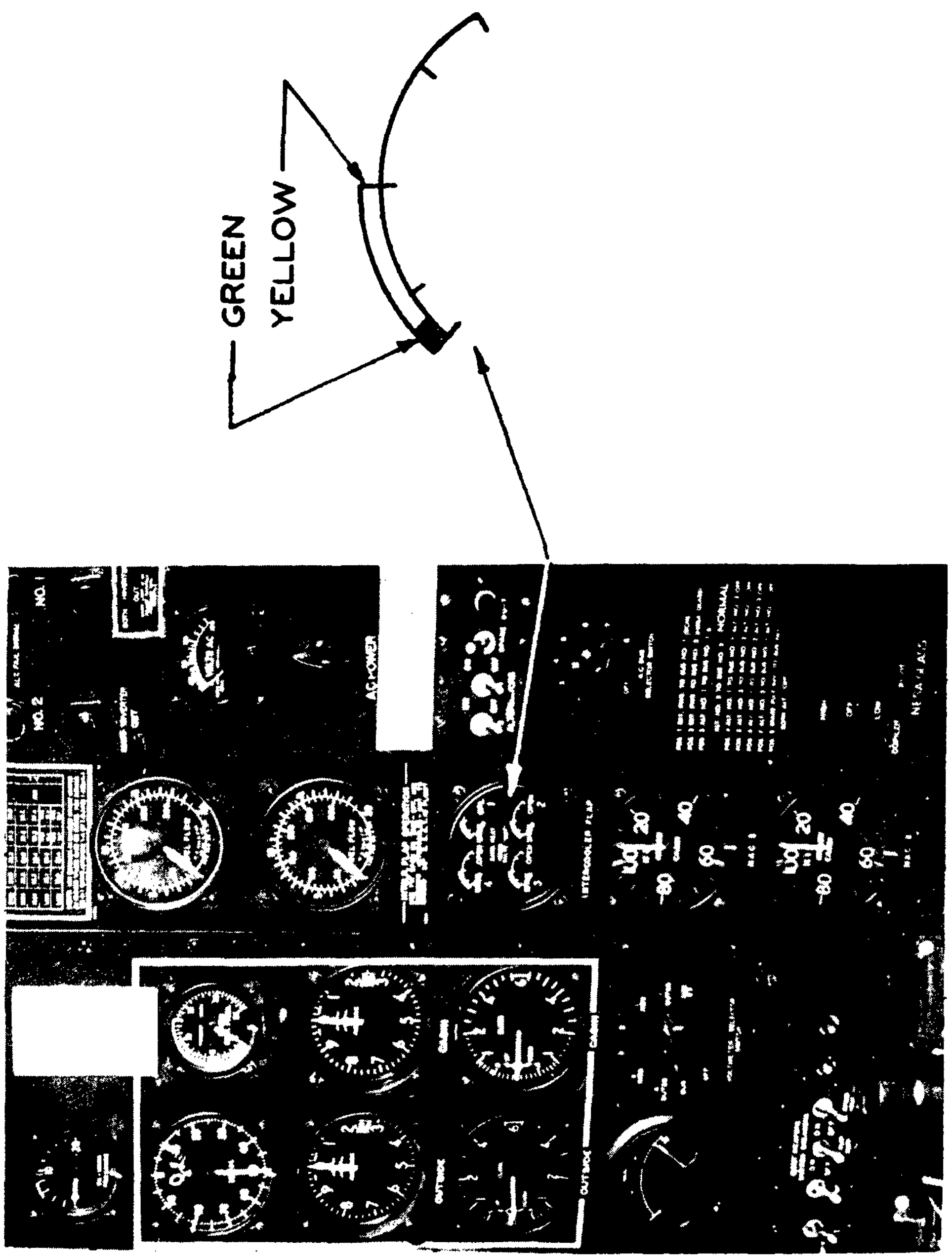


FIGURE II.4

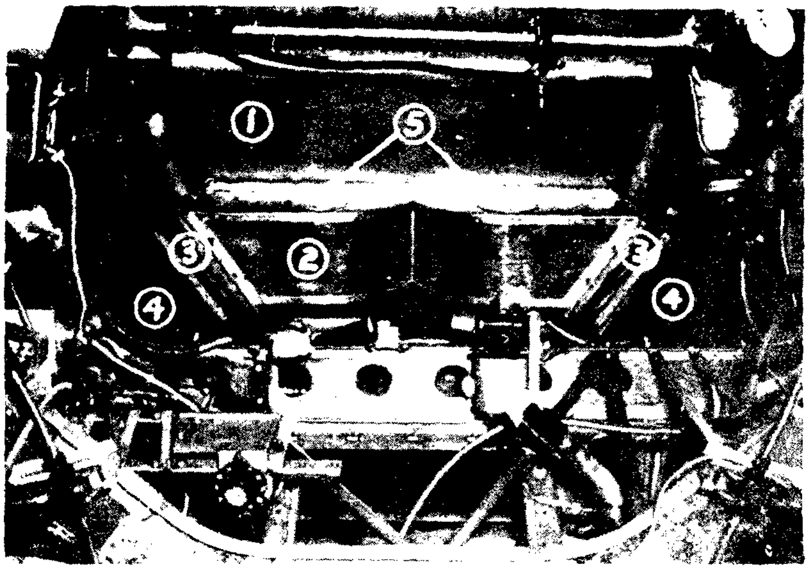
MODIFIED INTERCOOLER EXIT SHUTTER INDICATOR a slightly higher heat rise than that available on Engines 1 and 4 which was attributed to the difference in ducting between inboard and outboard engines and shorter valve moment arm resulting in better sealing. Engine 3 was selected to obtain the missing airflow data, and rerun of temperature data on which to base development of the design equations, since it represented the best ducting arrangement, and simplified instrumentation. Details of the installation on Engine 3 are shown in Figure II.5, II.6, and II.7. AF drawings for this installation are listed in Table II.1.

Description of Instrumentation

The temperature instrumentation on engine 3 was identical to that used in previous tests of the interwarmer system and as described in Reference 2,4, and 5 with the additional thermocouples in the exhaust manifold near the firewall and near the turbo. The temperature instrumentation was so designed so as to reveal heat losses and gains throughout the system. A verbal description of each thermocouple location, together with the symbol to be used in the development of equations, is given in Table II.2 and shown on Figure II.8. Thermocouples were connected to an automatic Brown Recorder shown in Figure II.9 located in the navigator's compartment. This recorder had an iron-constantan range of -50°C to +650°C and a chromel-alumel range of +400°C to +1400°C. All thermocouples were of a bare wire iron-constantan type except for those in the exhaust system which were chromel-alumel. Typical duct thermocouple installations are shown in Figures II.10 and II.11, and those of the carburetor top deck screen, which are also typical of those in the inlet and outlet of the intercooler in the interwarmer flow, are shown in Figure II.12.

Airflow instrumentation was established on Engine 3 so as to give the velocity of the air at definite cross sections in the induction system, interwarmer system, and exhaust system. The weight airflow could then be computed from $W = \rho ua$. The instrumentation for measuring induction system air velocity consisted of static pressures at chambers A and B of the carburetor in order to obtain the mean suction differential (MSD). This can then be read off the engine manufacturer's charts to obtain the weight airflow. In order to check this method of measurement of induction system airflow a 3 rake pitot tube, shown in Figure II.12, and a static tube were installed at the carburetor top deck. Still another check was to provide a static tube at the bottom deck, and together with the static pressure at the top deck would allow simulation of the airflow in the laboratory. This would be done by mounting the carburetor in the laboratory and flowing a known amount of air through until the static pressures agreed with those measured for any power setting.

The air velocity through the interwarmer system appeared to be more difficult to measure because of more irregular shaped ducting. For this reason, it was decided to make checks at three locations, one on each side of the hot air manifold and under the intercooler. A 3 rake pitot and a static tube were installed at the former location, and a pitot-static tube was installed at the center of each quadrant of the area below the intercooler.



(1) Modified Intercooler Cooling Air Duct

(2) Manifold Assembly

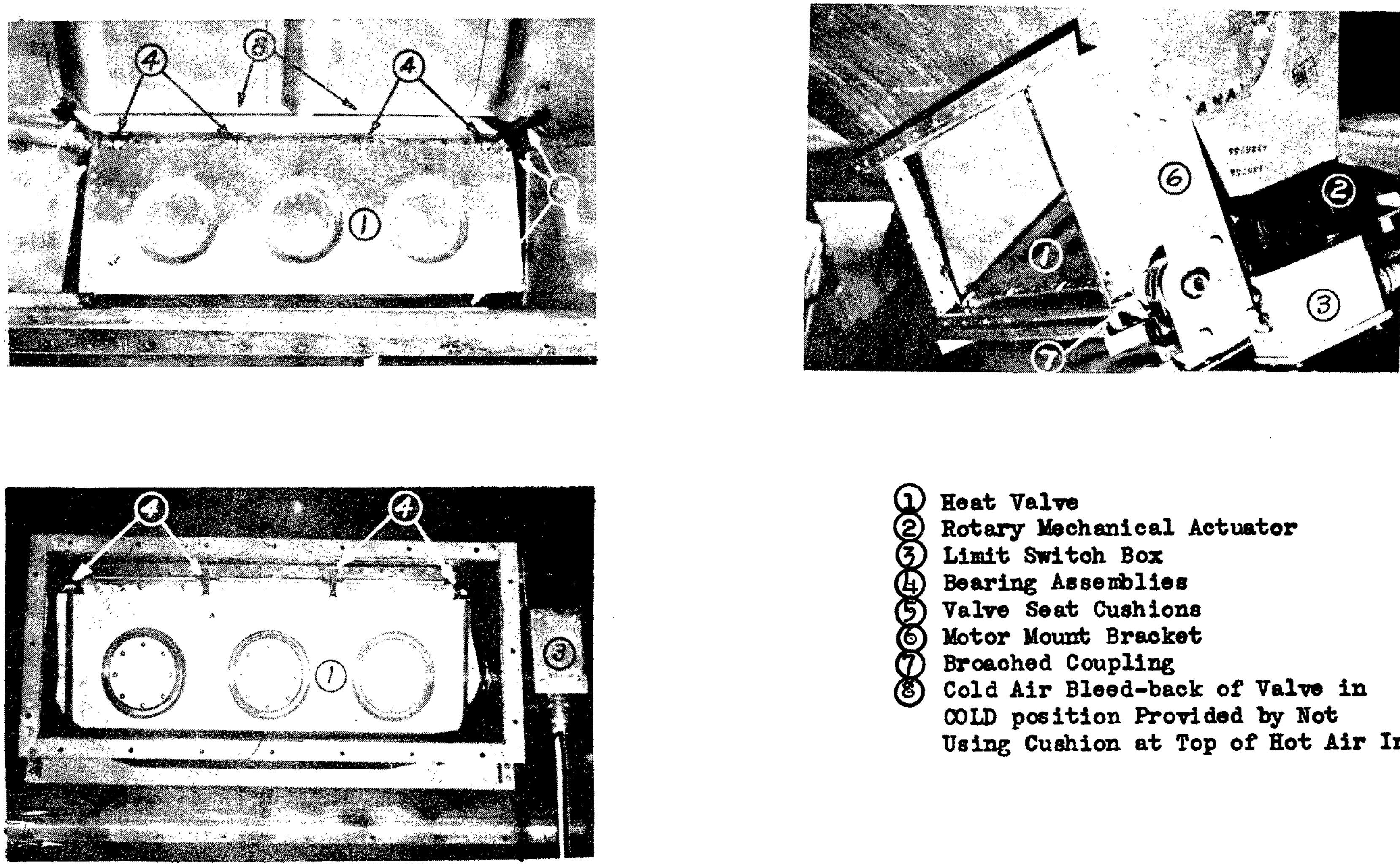
(3) Flexible Connector Assembly

(4) Elbow Assembly

(5) Heat Valve Inspection Panels

FIGURE II.5

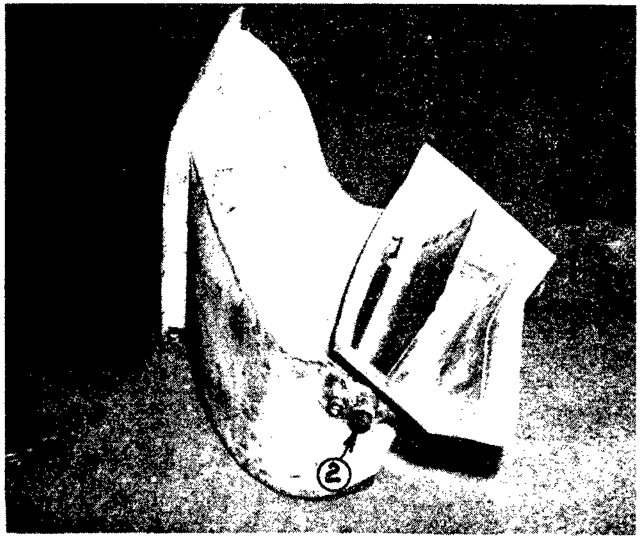
INTERWARMER INDUCTION AIR HEATING
SYSTEM INSTALLATION ON ENGINE 3

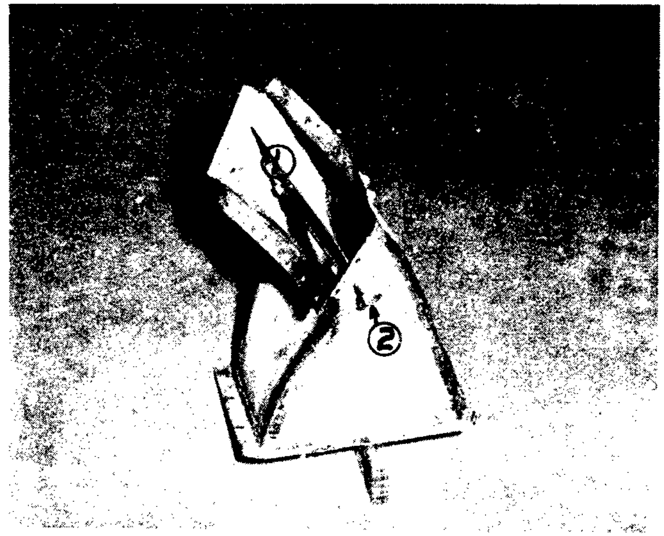


1 Heat Valve
2 Rotary Mechanical Actuator
3 Limit Switch Box
4 Bearing Assemblies
5 Valve Seat Cushions
6 Motor Mount Bracket
7 Broached Coupling
8 Cold Air Bleed-back of Valve in COLD position Provided by Not Using Cushion at Top of Hot Air Inlet

FIGURE II.6

MODIFIED INTERCOOLER COOLING AIR DUCT - ENGINE 3





OUTBOARD SIDE

INBOARD SIDE

(1) Fire Valve

(2) Fuse Plug Assembly

FIGURE II.7

ELBOW ASSEMBLY - ENGINE 3

TABLE II.1

AIR FORCE DRAWING LIST APPLICABLE TO
INTERWARMER INDUCTION AIR HEATING SYSTEM ON ENGINE 3
B-29 SERIAL NO. 45-21698

Number	Title
48J20920	Heating System - Induction Air, Interwarmer, Installation of
48B20914	Panel Assembly - Control, Induction Air Heating System
48B20915	Plate - Mounting, Control Panel, Induction Air Heating System
48J20921	Duct Assembly - Cool Air, Induction Air Heating System, Inboard Engine, Modification of
48E20922	Duct Assembly - Air Control, Induction Air Heating System, Inboard and Outboard Engines
48J20923	Elbow Assembly - Inboard Engine, Induction Air Heating System, Inboard Side
48J20924	Elbow Assembly - Inboard Engine, Induction Air Heating System, Outboard Side
48D20925	Duct Assembly - Take-off, Induction Air Heating System, Inboard Engine, Modification of
48D20926	Valve Assembly - Inboard Engine, Induction Air Heating System
48B20927	Dial - Intercooler Flap Position Indicator, Induction Air Heating System, Modification of
48D20928	Manifold Assembly - Inboard Engine, Induction Air Heating System
48D20929	Motor and Limit Switch Assembly - Induction Air Heating System, Inboard and Outboard Engines
48C20930	Bracket - Motor Mount, Induction Air Heating System, Inboard Engine
48C20931	Connector Assembly - Flexible, Induction Air Heating System, Inboard Engine
48T20932	Shaft - Inboard Engine Valve, Induction Air Heating System
48B20933	Gasket - Elbow to Manifold, Induction Air Heating System, Inboard Engine

48B20934	Gasket - Manifold to Duct, Induction Air Heating System, Inboard Engine
48B20935	Bearing Assembly - Cool Air Duct, Induction Air Heating System, Inboard Engine
48A20936	Coupling - Cool Air Duct, Induction Air Heating System, Inboard and Outboard Engines
48B20938	Name Plate - Control Panel, Induction Air Heating System
48C20939	Wiring Diagram - Induction Air Heating System, Schematic
49B21552	Arm - Control, Fire Valve, Induction Air Heating System
49B21555	Boss - Fire Valve Fuse, Induction Air Heating System
49B21556	Spring - Fire Valve, Induction Air Heating System
49B21558	Plug Assembly - Fire Valve Fuse, Induction Air Heating System
49A21559	Guide - Fire Valve Spring, Induction Air Heating System
49C21560	Valve - Fire, Outboard Side, Inboard Engine Elbow, Induction Air Heating System
49C21561	Valve - Fire, Inboard Side, Inboard Engine Elbow, Induction Air Heating System
50D26072	Elbow Assembly - Fire Valve, Outboard Side Inboard Engine Elbow, Induction Air Heating System
50D26073	Elbow Assembly - Fire Valve, Inboard Side Inboard Engine Elbow, Induction Air Heating System
50B26074	Shaft - Fire Valve, Induction Air Heating System, 11.5 Inch
50B26075	Shaft - Fire Valve, Induction Air Heating System, 10.5 Inch
50B26076	Boss - Valve Shaft, Induction Air Heating System, Straight
50B26077	Boss - Fire Valve Spring, Induction Air Heating System, Straight
50B26078	Boss - Valve Shaft, Induction Air Heating System, 20 Degrees

TABLE II.2

TEMPERATURE INSTRUMENTATION

Induction System

Symbol	Location
$T_{1a}(1)$	Inboard turbo duct-inlet side
$T_{2a}(1)$	Inboard turbo duct-outlet side near turbo
$T_{1a}(2)$	Outboard turbo duct-inlet side
$T_{2a}(2)$	Outboard turbo duct-outlet side near turbo
$T_{3a}(1)$	Inboard side turbo duct just ahead of intercooler
$T_{3a}(2)$	Outboard side turbo duct just ahead of intercooler
$T_{4a}(1)$	Right side top on carburetor side of intercooler
$T_{4a}(2)$	Right side bottom on carburetor side of intercooler
$T_{4a}(3)$	Left side top on carburetor side of intercooler
$T_{4a}(4)$	Left side bottom on carburetor side of intercooler
$T_{5a}(1)$	Carburetor top deck left side front
$T_{5a}(2)$	Carburetor top deck right side front
$T_{5a}(3)$	Altitude compensator
$T_{5a}(4)$	Carburetor top deck left side rear
$T_{5a}(5)$	Carburetor top deck right side rear
$T_{6a}(1)$	Carburetor bottom deck left side center
$T_{6a}(2)$	Carburetor bottom deck right side center

Interwarmer Induction Air Heating System

$T_g(1)$	Inboard exhaust manifold - near firewall
$T_{1g}(1)$	Inboard exhaust manifold - near turbo
$T_g(2)$	Outboard exhaust manifold - near firewall
$T_{1g}(2)$	Outboard exhaust manifold - near turbo
$T_{1h}(1)$	Hot air duct from supercharger cover shroud inboard side-temperature of airflow

$T_{1h}(2)$	Hot air duct from supercharger cover shroud outboard side - temperature of airflow
$T_{2h}(1)$	Hot air manifold left side just prior to entering modified duct valve opening
$T_{2h}(2)$	Hot air manifold right side just prior to entering modified duct valve opening
$T_{3h}(1)$	Right side front just below intercooler tubes
$T_{3h}(2)$	Right side rear just below intercooler tubes
$T_{3h}(3)$	Left side front just below intercooler tubes
$T_{3h}(4)$	Left side rear just below intercooler tubes
$T_{4h}(1)$	Right side front just above intercooler tubes
$T_{4h}(2)$	Right side rear just above intercooler tubes
$T_{4h}(3)$	Left side front just above intercooler tubes
$T_{4h}(4)$	Left side rear just above intercooler tubes
T_a	Intake duct entrance - Free Air Temperature

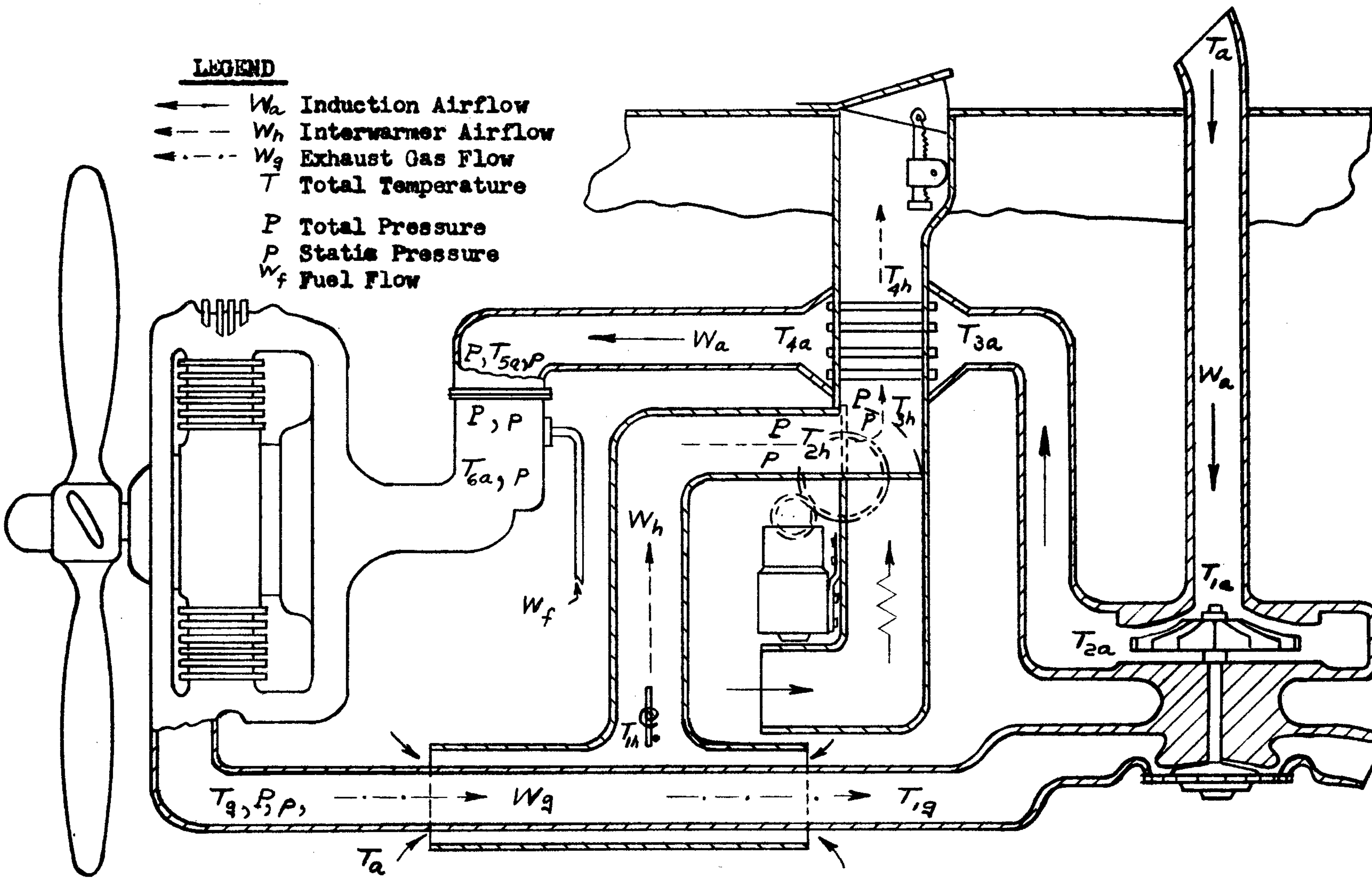


FIGURE II.8

SCHEMATIC LOCATION OF INSTRUMENTATION
on B-29 SERIAL NUMBER 45-21698

FIGURE II.9

BROWN RECORDER INSTALLATION

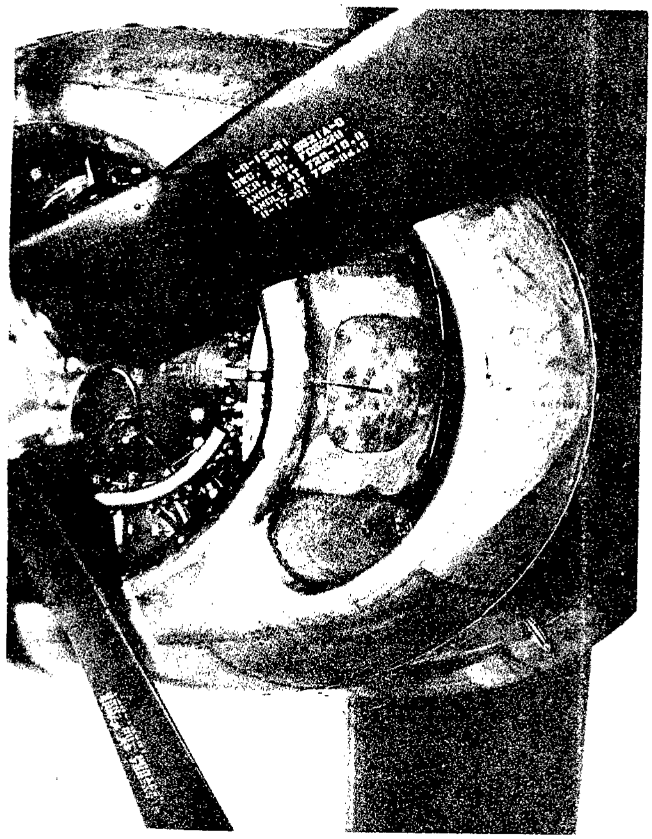


FIGURE II.10

FREE AIR TEMPERATURE - INDUCTION SYSTEM INLET

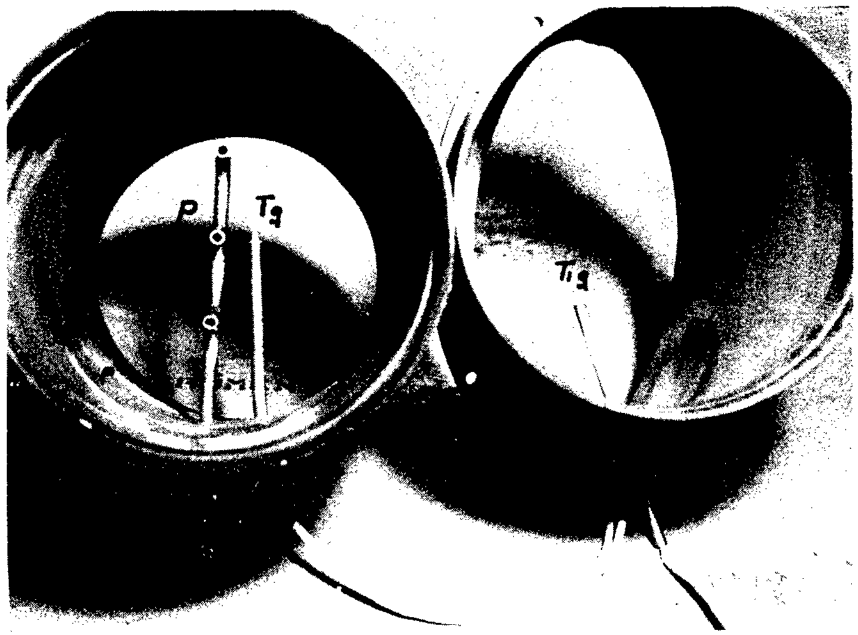


FIGURE II.11

TYPICAL DUCT THERMOCOUPLE AND PITOT-STATIC TUBE INSTALLATIONS - EXHAUST MANIFOLD

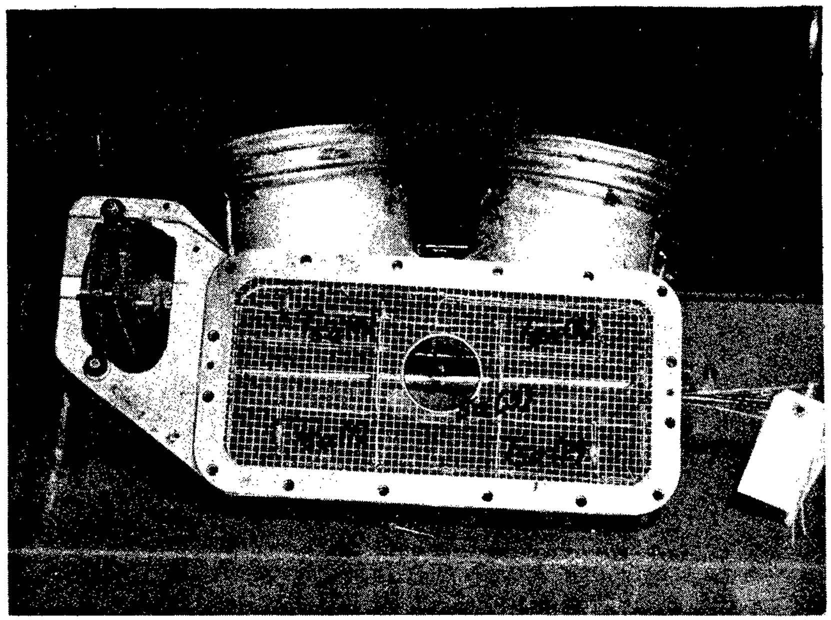


FIGURE II.12

CARBURETOR TOP DECK THERMOCOUPLE
AND PITOT TUBE INSTALLATION

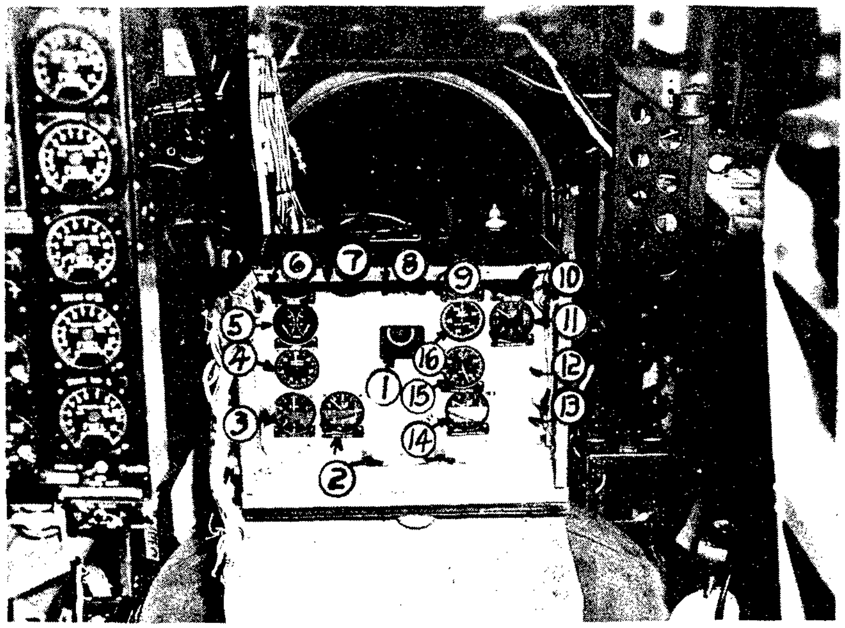
The velocity of the exhaust gas through each of the two exhaust manifolds was to be determined by installing a 3 rake pitot and a static tube in a straight section of each manifold. This is shown in Figure II.11 and is typical of all 3 rake pitot-static tube installations. A check on exhaust gas weight flow is available from the relationship $W_g = W_a + W_f$. Hence the fuel weight flow was measured by an electric fuel flow counter which when added to the induction airflow obtained as described above would provide a check on the exhaust gas weight flow.

All instruments, other than temperature measuring, were installed in a photo observer and mounted above the forward gun turret as shown in Figure II.13. Pitot-static tubes of Engine 3 were connected to applicable pressure gages in the photo observer by copper tubing. Such aircraft instruments as airspeed indicator, altimeter, manifold pressure gage, and tachometer indicator were paralleled into the corresponding system in the aircraft.

Test Procedures

Flight operations accomplished on B-29, Serial No 45-21698, conformed to the Handbook of Flight Operation Instruction, Technical Order AN 01-20EJA-1, and to current local air base restrictions. Previous flight tests accomplished at Ladd Air Force Base, Alaska, were made on all engines according to the procedure outlined below and discussed in detail in Reference 2. The latest flight test to obtain the exhaust gas temperatures, airflow, and fuel flow measurements which were not obtained previously, together with a rerun of temperatures at all locations described above, was accomplished only on Engine 3. This engine had been selected as the basis for the development of design equations.

The conditions at which data were recorded were as listed in Table II.3. For each of the twenty-five conditions listed above, data were recorded with the interwarmer system for engine 3 "OFF" and then with the system "ON". In each case, data were recorded only after power settings and temperature conditions had become stabilized. When the interwarmer system was "OFF", the intercooler shutter indicator read "SHUT", and when heat was "ON", the indicator for the shutter was at the end of the green range on the gage which is the "1/3 OPEN" position. When a power setting was set up on Engine 3, it was set upon all four engines since airspeed, which directly affected the carburetor air temperature rise, had to correspond to the power being developed for true results. At least two photo frames and thermocouple surveys were taken after power and temperature stabilization had been achieved at each of the twenty-five aforementioned conditions.



1. Camera
2. Altitude - Type C-12 Altimeter
3. Engine RPM - Tachometer Indicator
4. Manifold Pressure - Standard Gage
5. P-p Inboard and Outboard Exhaust Manifold - Duel Autosyn Differential Pressure Indicator
6. Carburetor Chambers A (p) and B (P) - Type F-1 Airspeed Indicator
7. P-p Carburetor Top Deck - Type F-1 Airspeed Indicator
8. P-p Inboard Side of Manifold - Airspeed Indicator 0 to 150 mph
9. P-p Outboard Side of Manifold - Airspeed Indictor 0 to 150 mph
10. p Carburetor Bottom Deck - Type C-12 Altimeter
11. p Carburetor Top Deck - Type C-12 Altimeter
12. Fuel Flow Counter
13. Camera Counter
14. p Duct Below Interwarmer - Type C-12 Altimeter
15. Airspeed - Type F-1 Airspeed Indicator
16. P Duct Below Interwarmer - Type -20 to 80 in H_2O Gage

FIGURE II.13

PHOTO-OBSERVER INSTALLATION

TABLE II.3

TEST CONDITIONS

Position or Altitude ft	Engine Speed rpm	Manifold Pressure in.hg.	Nominal Power % N.R.
Warm-up	1000-1300	20	
Taxi	----	--	
Take-off	2800	49	
Pattern	2400	25	
Approach	2400	20	
2000	2400	41.8	100
2000	2200	35	80
2000	2100	32.8	65
2000	1700	30.8	50
7500	2400	40.9	100
7500	2200	33.6	80
7500	2100	31	65
7500	1700	28.8	50
15000	2400	40.3	100
15000	2200	32.6	80
15000	2100	29.7	65
15000	1700	27.3	50
20000	2400	40.2	100
20000	2200	32.4	80
20000	2100	29.4	65
20000	1700 or 1750*	26.2	50
25000	2400	40.2	100
25000	2200	32.4	80
25000	2100	29.3	65
25000	1700 or 1750*	26	50

*May get surging

CHAPTER III - TEST RESULTS

The performance of the interwarmer induction air heating system had been established and the final configuration determined by test and results described in Reference 2. The tests described in Chapter II were performed to obtain data for design purposes. Initial tests were run 11 February 1952. These tests provided only the temperature data inasmuch as the photo observer which was used to measure the airflow data was not functioning during tests and passed unnoticed by the flight engineer. This was discovered after the photo observer film was developed. Before tests could be rerun, the Directorate of Flight and All Weather Testing Control Office assigned the aircraft to the Aircraft Radiation Laboratory, Directorate of Laboratories, because of a 1A priority project. The test was finally rerun on 30 April and 1 May 1952 in order to get both the temperature and the airflow data. The results of this latter test are described in Reference 9. Comparison of the results of both tests indicates that the temperature data of the initial tests were the best, and that all methods of airflow determination were inadequate except for the mean suction differential (MSD) method for induction system mass airflow determination. The inadequacy of these latter results was primarily due to the high outside air temperatures encountered which prevented operation of the system to full capacity. Since the initial temperature data are complete enough to allow determination of all enthalpy changes through the induction system and through the interwarmer system, it is sufficiently complete to allow determination of airflow ratios between the various systems. These temperature data are presented in Table III.1.

The instrumentation and tests of Reference 2 were designed so as to determine the best configuration and the performance of the system in meeting the requirements of the Air Force at that time. These requirements were included in the Handbook of Instructions of Aircraft Designers, AMC Manual 80-1, and are summarized as follows:

a. Sufficient heat shall be available to raise the intake air from -40°F (-40°C) to +70°F (+21.1°C) within 30 seconds at 65% of normal sea level rated power. In turbosupercharged aircraft, this requirement must be met without the aid of heat obtainable from the turbosupercharger.

b. Sufficient heat shall be available to raise the intake air from -65°F (-53.8°C) to 0°F (-17.8°C) at 25% rated power.

c. Control shall be provided so that heated air can be metered to the carburetor in increments not larger than 20°F (11.1°C).

d. With the control in the full "Hot" position, the static pressure at the carburetor top deck shall not be reduced by more than 2 in. hg. below the pressure existing when the control is in the full "Cold" position.

e. The maximum temperature variation between the altitude compensating valve and the average carburetor top deck temperature shall not exceed 5°F (2.8°C).

TABLE III.1
TEMPERATURE SURVEYS

Pressure Altitude Ft	Nominal Power % N.R.	Valve Position	T_a	Induction System $T_{1a}(1)$	$T_{1a}(2)$	T_{1a}	$T_{2a}(1)$	$T_{2a}(2)$	T_{2a}	$T_{3a}(1)$	$T_{3a}(2)$	T_{3a}	$T_{4a}(1)$	$T_{4a}(2)$	$T_{4a}(3)$	$T_{4a}(4)$	T_{4a}	$T_{5a}(1)$	$T_{5a}(2)$	$T_{5a}(3)$	$T_{5a}(4)$	$T_{5a}(5)$	T_{5a}	$T_{6a}(1)$	$T_{6a}(2)$	T_{6a}
2000	100	Cold	1	2	*2	2	7	8	8	7	8	8	6	6	8	5	6	8	7	7	7	7	7	5	5	5
	100	Hot	5	5		5	10	11	11	10	10	20	24	26	25	37	28	25	33	33	30	5	25	26	25	26
	80	Cold	0	4		4	7	8	8	7	7	7	7	7	8	7	7	6	6	6	6	6	6	9	6	8
	80	Hot	0	2		2	5	6	6	5	5	5	29	26	39	27	30	26	24	31	31	30	28	25	23	24
	65	Cold	0	1		1	4	5	5	3	4	4	4	4	4	4	4	4	4	4	3	3	4	3	1	2
	65	Hot	0	1		1	4	5	5	4	5	5	30	35	31	46	35	33	31	39	39	37	36	32	31	32
	50	Cold	3	2		2	4	5	5	4	4	4	4	5	5	5	5	6	5	6	4	4	5	5	5	5
	50	Hot	2	1		1	3	4	4	4	4	4	33	38	34	48	38	35	34	42	42	39	38	35	35	35
7500	100	Cold	3	4			21	25	23	21	25	23	20	19	20	16	19	20	19	18	19	19	19	20	20	20
	100	Hot	5	6			24	28	26	24	26	25	37	43	39	51	43	40	39	46	45	44	43	43	43	43
	80	Cold	3	2			15	18	17	15	17	16	14	13	15	11	14	14	14	14	13	13	14	13	12	13
	80	Hot	3	3			15	18	17	15	17	16	35	40	35	50	40	37	35	45	41	41	40	37	36	37
	65	Cold	3	4			15	17	16	15	17	16	13	13	14	11	13	14	14	23	12	12	15	6	6	6
	65	Hot	1	2			13	15	14	13	15	14	38	46	39	55	45	40	40	54	46	46	45	43	41	42
	50	Cold	0	0			8	9	9	11	9	10	7	7	8	6	7	9	8	15	7	7	9	9	8	9
	50	Hot	1	1			10	11	11	10	11	11	39	46	39	51	44	39	39	50	47	46	44	43	42	43
15000	100	Cold	-5	-4			36	42	39	36	41	39	32	30	34	21	29	31	31	28	29	29	30	32	32	32
	100	Hot	-5	-5			37	43	40	36	42	39	44	48	43	46	45	42	42	50	45	46	45	46	46	46
	80	Cold	-6	-5			30	34	32	30	33	32	25	22	27	15	22	25	25	21	21	21	23	20	20	20
	80	Hot	-6	-5			29	33	31	30	33	32	43	49	43	54	47	43	43	53	50	50	48	44	43	44
	65	Cold	-8	-6			25	29	27	26	28	27	20	19	23	18	19	20	20	24	17	17	20	17	16	17
	65	Hot	-9	-9			23	27	25	25	26	26	41	46	41	53	45	41	41	55	47	47	44	41	40	41
	50	Cold	-10	-9			15	17	16	15	16	16	10	8	12	5	9	10	10	13	8	7	10	10	10	10
	50	Hot	-10	-8			15	16	16	15	15	15	43	50	43	60	49	43	43	60	54	51	50	46	46	46
20000	100	Cold	-11	-11			48	44	46	48	54	51	43	39	45	28	39	41	41	36	38	37	39	40	40	40
	100	Hot	*3																							
	80	Cold	-14	-13			39	44	42	39	42	41	33	29	36	18	29	31	31	26	26	26	28	26	26	26
	80	Hot	-15	-14			36	41	39	38	40	39	45	50	45	48	47	43	44	62	48	47	49	45	45	45
	65	Cold	-15	-15			35	38	37	35	36	36	28	25	31	14	25	26	27	24	21	21	24	22	22	22
	65	Hot	-15	-13			35	38	37	36	36	36	48	51	46	53	49	44	46	57	50	50	49	45	45	45
	50	Cold	-16	-15			25	25	25	26	25	26	19	15	21	5	15	17	18	18	12	12	15	15	15	15
	50	Hot	-18	-17			23	23	23	23	22	23	50	55	50	66	55	50	49	76	61	56	58	52	54	53
25000	100	Cold	-22	-21			57	65	61	58	63	61	35	30	40	15	30	35	35	28	29	28	31	15	40	28
	100	Hot	*3																							
	80	Cold	-22	-21			49	52	51	50	51	51	42	36	45	20	36	38	39	32	34	32	35	34	34	34
	80	Hot	-23	-22			49	52	51	50	51	51	54	56	53	52	54	48	50	58	54	53	53	49	49	49
	65	Cold	-24	-23			45	47	46	46	45	46	38	33	41	16	32	34	35	27	26	27	30	29	29	29
	65	Hot	-26	-25			43	45	44	43	43	43	48	50	45	41	46	40	44	50	46	43	44	45	45	45
	50	Cold	*3																							
	50	Hot	*3																							

Pressure Altitude Ft	Nominal Power % N.R.	Valve Position	$T_g(1)$	$T_g(2)$	T_g	$T_{1g}(1)$	$T_{1g}(2)$	T_{1g}	Interwarmer System $T_{1h}(1)$	$T_{1h}(2)$	T_{1h}	$T_{2h}(1)$	$T_{2h}(2)$	T_{2h}	T_{3h}
2000	100	Cold	828	838	839	839	838	826	6	6	6	5	5	5	
	100	Hot	825	*2		817	827	822	65	73	69	64	73	69	
	80	Cold	865			853	864	859	10	10	10	8	9	9	
	80	Hot	854			842	849	846	63	71	67	62	72	67	
	65	Cold	855			842	847	845	6	7	7	5	5	5	
	65	Hot	916			896	908	902	73	84	79	72	89	81	
	50	Cold	890			868	874	871	7	7	7	5	5	5	
	50	Hot	871			848	860	854	68	78	73	68	80	74	[illegible]
7500	100	Cold	845			838	850	844	5	4	5	4	4	4	
	100	Hot	860			851	862	857	76	90	83	77	90	84	[illegible]
	80	Cold	867			855	860	858	9	9	9	8	7	8	
	80	Hot	860			848	854	851	75	87	81	75	87	81	[illegible]
	65	Cold	937			920	925	923	6	4	5	4	3	4	
	65	Hot	929			908	918	913	84	100	90	85	101	93	[illegible]
	50	Cold	887			865	875	870	9	8	9	6	6	6	
	50	Hot	886			864	874	869	81	92	87	83	94	89	[illegible]
15000	100	Cold	854			845	860	853	3	2	3	1	0	1	[illegible]
	100	Hot	853			844	858	851	77	93	85	77	93	85	[illegible]
	80	Cold	869			858	861	860	1	1	1	0	0	0	[illegible]
	80	Hot	860			848	852	850	75	91	83	75	92	84	[illegible]
	65	Cold	856			845	850	848	1	1	1	0	0	0	[illegible]
	65	Hot	850			838	844	841	74	90	82	75	91	83	[illegible]
	50	Cold	888			866	888	877	2	2	2	-1	1	0	[illegible]
	50	Hot	891			872	888	880	89	91	90	91	103	97	[illegible]
20000	100	Cold	863			855	867	861	-2	-4	-3	-4	-5	-5	[illegible]
	100	Hot													
	80	Cold	877			866	873	870	-5	-6	-6	-7	-7	-7	[illegible]
	80	Hot	873			860	869	865	78	95	87	79	96	88	[illegible]
	65	Cold	866			855	857	856	-5	-5	-5	-7	-7	-7	[illegible]
	65	Hot	863			851	856	854	77	95	86	80	97	89	[illegible]
	50	Cold	883			868	892	880	-7	-7	-7	-9	-9	-9	[illegible]
	50	Hot	890			875	890	883	100	110	105	100	114	107	[illegible]
25000	100	Cold	863			855	871	863	-17	-17	-17	35	30	33	[illegible]
	100	Hot													
	80	Cold	875	893	884	863	873	868	-13	-14	-14	-15	-15	-15	[illegible]
	80	Hot	873			865	875	870	78	97	88	77	99	83	[illegible]
	65	Cold	875			864	864	864	-10	-10	-10	-14	-13	-14	[illegible]
	65	Hot	865			852	853	853	72	86	79	70	90	80	[illegible]
	50	Cold													
	50	Hot													

*Notes
1. All temperatures °C
2. Thermocouple inoperative
3. No data taken due to effect on flight conditions.
4. The hot data for 65% N.R. Power for all T_{3h}'s read low. This was probably due to switching valve to Cold before s
5. The data under Columns T_{1a}, T_{2a}, T_{3a}, T_{4a}, T_{5a}, T_{6a}, T_g, T_{1g}, T_{1h}, T_{2h}, T_{3h}, and T_{4h} are averages of the data taken lacking at $T_{1a}(2)$ and $T_g(2)$, $T_{1a}(1)$ and $T_{2a}(1)$ were used for T_{1a} and T_{2a}, and $T_g(1)$ and $T_{1g}(1)$ were used for T_g ar

TABLE III.1
TEMPERATURE SURVEYS

$T_{1a}(2)$	T_{2a}	$T_{3a}(1)$	$T_{3a}(2)$	T_{3a}	$T_{4a}(1)$	$T_{4a}(2)$	$T_{4a}(3)$	$T_{4a}(4)$	T_{4a}	$T_{5a}(1)$	$T_{5a}(2)$	$T_{5a}(3)$	$T_{5a}(4)$	$T_{5a}(5)$	T_{5a}	$T_{6a}(1)$	$T_{6a}(2)$	T_{6a}	$T_g(1)$	$T_g(2)$	T_g	$T_{1g}(1)$	$T_{1g}(2)$	T_{1g}	$T_{1h}(1)$	$T_{1h}(2)$	T_{1h}	$T_{2h}(1)$	$T_{2h}(2)$	T_{2h}	$T_{3h}(1)$	$T_{3h}(2)$	$T_{3h}(3)$	$T_{3h}(4)$	T_{3h}	$T_{4h}(1)$	$T_{4h}(2)$	$T_{4h}(3)$	$T_{4h}(4)$	T_{4h}
Induction System																						Interwarmer System																		
8	8	7	8	8	6	6	8	5	6	8	7	7	7	7	7	5	5	5	828	838	839	839	838	826	6	6	6	5	5	5	4	4	4	4	4	5	6	5	6	6
11	11	10	10	20	24	26	25	37	28	25	33	33	30	5	25	26	25	26	825	*2		817	827	822	65	73	69	64	73	69	53	57	56	59	56	28	28	33	31	30
8	8	7	7	7	7	7	8	7	7	6	6	6	6	6	6	9	6	8	865			853	864	859	10	10	10	8	9	9	5	5	5	5	5	7	7	6	8	7
6	6	5	5	5	29	26	39	27	30	26	24	31	31	30	28	25	23	24	854			842	849	846	63	71	67	62	72	67	50	54	55	60	55	27	26	30	30	28
5	5	3	4	4	4	4	4	4	4	4	4	4	3	3	4	3	1	2	855			842	847	845	6	7	7	5	5	5	3	3	3	4	3	4	4	4	4	4
5	5	4	5	5	30	35	31	46	35	33	31	39	39	37	36	32	31	32	916			896	908	902	73	84	79	72	89	81	4	37	39	39	30	31	33	46	31	33
5	5	4	4	4	4	5	5	5	5	6	5	6	4	4	5	5	5	5	890			868	874	871	7	7	7	5	5	5	3	3	3	3	3	5	5	4	5	5
4	4	4	4	4	33	38	34	48	38	35	34	42	42	39	38	35	35	35	871			848	860	854	68	78	73	68	80	74	58	61	62	65	62	40	35	41	38	39
25	23	21	25	23	20	19	20	16	19	20	19	18	19	19	19	20	20	20	845			838	850	844	5	4	5	4	4	4	5	5	5	6	5	17	19	15	20	18
28	26	24	26	25	37	43	39	51	43	40	39	46	45	44	43	43	43	43	860			851	862	857	76	90	83	77	90	84	65	69	69	71	69	41	41	46	44	43
18	17	15	17	16	14	13	15	11	14	14	14	14	13	13	14	13	12	13	867			855	860	858	9	9	9	8	7	8	4	4	4	4	4	13	14	11	15	14
18	17	15	17	16	35	40	35	50	40	37	35	45	41	41	40	37	36	37	860			848	854	851	75	87	81	75	87	81	63	66	66	70	66	40	37	44	40	40
17	16	15	17	16	13	13	14	11	13	14	14	23	12	12	15	6	6	6	937			920	925	923	6	4	5	4	3	4	5	5	5	6	5	12	13	11	15	13
15	14	13	15	14	38	46	39	55	45	40	40	54	46	46	45	43	41	42	929			908	918	913	84	100	90	85	101	93	73	77	75	79	76	44	43	50	45	46
9	9	11	9	10	7	7	8	6	7	9	8	15	7	7	9	9	8	9	887			865	875	870	9	8	9	6	6	6	2	3	2	3	3	9	10	8	12	10
11	11	10	11	11	39	46	39	51	44	39	39	50	47	46	44	43	42	43	886			864	874	869	81	92	87	83	94	89	72	76	74	76	75	43	42	50	43	45
42	39	36	41	39	32	30	34	21	29	31	32	28	29	29	30	32	32	32	854			845	860	853	3	2	3	1	0	1	-3	-1	-2	0	-2	26	30	29	32	29
43	40	36	42	39	44	48	43	46	45	42	42	50	45	46	45	46	46	46	853			844	858	851	77	93	85	77	93	85	63	68	67	69	66	41	45	48	46	45
34	32	30	33	32	25	22	27	15	22	25	25	21	21	21	23	20	20	20	869			858	861	860	1	1	1	0	0	0	-3	-3	-3	-2	-3	21	25	18	25	22
33	31	30	33	32	43	49	43	54	47	43	43	53	50	50	48	44	43	44	860			848	852	850	75	91	83	75	92	84	64	68	68	72	68	46	45	48	47	47
29	27	26	28	27	20	19	23	13	19	20	20	24	17	17	20	17	16	17	856			845	850	848	1	1	1	0	0	0	-4	-4	-5	-4	-4	20	23	16	25	21
27	25	25	26	26	41	46	41	53	45	41	41	55	47	47	44	41	40	41	850			838	844	841	74	90	82	75	91	83	64	69	67	72	68	45	43	48	45	45
17	16	15	16	16	10	8	12	5	9	10	10	13	8	7	10	10	10	10	888			866	888	877	2	2	2	-1	1	0	-6	-6	-6	-5	-6	10	13	7	15	11
16	16	15	15	15	43	50	43	60	49	43	43	60	54	51	50	46	46	46	891			872	888	880	89	91	90	91	103	97	75	83	80	85	81	48	45	53	47	48
44	46	48	54	51	43	39	45	28	39	41	41	36	38	37	39	40	40	40	863			855	867	861	-2	-4	-3	-4	-5	-5	-9	-8	-8	-5	-8	36	41	33	55	41
44	42	39	42	41	33	29	36	18	29	31	31	26	26	26	28	26	26	26	877			866	873	870	-5	-6	-6	-7	-7	-7	-11	-9	-10	-9	-10	30	35	26	37	32
41	39	38	40	39	45	50	45	48	47	43	44	62	48	47	49	45	45	45	873			860	869	865	78	95	87	79	96	88	64	68	66	71	67	43	46	50	49	47
38	37	35	36	36	28	25	31	14	25	26	27	24	21	21	24	22	22	22	866			855	857	856	-5	-5	-5	-7	-7	-7	-12	-11	-12	-10	-11	25	30	22	32	27
38	37	36	36	36	48	51	46	53	49	44	46	57	50	50	49	45	45	45	863			851	856	854	77	95	86	80	97	89	66	73	70	75	71	46	48	53	50	49
25	25	26	25	26	19	15	21	5	15	17	18	18	12	12	15	15	15	15	883			868	892	880	-7	-7	-7	-9	-9	-9	-13	-11	-13	-11	-12	16	22	13	24	19
23	23	23	22	23	50	55	50	66	55	50	49	76	61	56	58	52	54	53	890			875	890	883	100	110	105	100	114	107	77	85	84	96	85	50	48	55	50	51
55	61	58	63	61	35	30	40	15	30	35	35	28	29	28	31	15	40	28	863			855	871	863	-17	-17	-17	35	30	33	-19	-19	-19	-19	-19	26	35	20	38	30
52	51	50	51	51	42	36	45	20	36	38	39	32	34	32	35	34	34	34	875	893	884	863	873	868	-13	-14	-14	-15	-15	-15	-18	-17	-19	-15	-17	31	39	28	40	35
52	51	50	51	51	54	56	53	52	54	48	50	58	54	53	53	49	49	49	873			865	875	870	78	97	88	77	99	83	60	68	69	71	65	45	50	50	51	49
47	46	46	45	46	38	32	41	16	32	34	35	27	26	27	30	29	29	29	875			864	864	864	-10	-10	-10	-14	-13	-14	-20	-16	-20	-16	-18	31	38	28	40	34
45	44	43	43	43	48	50	45	41	46	40	44	50	46	43	44	45	45	45	865			852	853	853	72	86	79	70	90	80	54	60	59	71	61	40	44	43	45	43

4. The hot data for 65% N.R. Power for all T_{3h}'s read low. This was probably due to switching valve to Cold before survey was complete.
5. The data under Columns T_{1a}, T_{2a}, T_{3a}, T_{4a}, T_{5a}, T_{6a}, T_g, T_{1g}, T_{1h}, T_{2h}, T_{3h}, and T_{4h} are averages of the data taken at those points. Since data were lacking at $T_{1a}(2)$ and $T_g(2)$, $T_{1a}(1)$ and $T_{2a}(1)$ were used for T_{1a} and T_{2a}, and $T_g(1)$ and $T_{1g}(1)$ were used for T_g and T_{1g}.

itions.

f. The hot air shall be entirely closed off when the cockpit control is in the full "Cold" position.

The requirements of paragraph a, above, have been modified in the latest revision of the HIAD recently released so that installation not susceptible to fuel evaporation, icing, i.e. fuel injection engines such as the R-3350-57 engines on the B-29 and engines having high pressure carburetors, would only have to maintain carburetor top deck temperatures of +40°F (+4.4°C) at an outside air temperature of -40°F (-40°C) at the same power. The requirement of paragraph b has been changed in that all installations must be capable of maintaining a carburetor top deck temperature of at least 0°F (-17.8°C) at -40°F (-40°C) outside air temperature at idling RPM at sea level. The change to the requirement of paragraph a has made it less severe while the change in the requirement of paragraph b has not made any appreciable difference.

While the test results showed the system did not completely meet the original HIAD requirements, the interwarmer system proved to be far superior than any of the other systems tested for turbosupercharged aircraft engines. The only requirement not met completely was that of paragraph a, above. The value of this requirement for installations not susceptible to fuel evaporation icing was questioned and it is noted that it has been changed in the latest revision of the HIAD as mentioned above. It is believed that the requirement of paragraph b and as revised is the most critical particularly for the prevention of power instability during low temperature operations, as well as for eliminating or preventing induction system icing. This requirement, as revised, however, does not allow a good basis for design due to the erratic airflow experienced during idling RPM. Since the interwarmer system showed in Reference 2 and present tests a CAT rise of at least 37°C above the OAT for any power setting in flight and a 30°C rise during engine warm-up, plus the fact that it was designed for continuous use rather than intermittent, it can be accepted as meeting the latest requirements. Therefore, the data obtained can be used for development of design equations.

The only problem remaining is to select the proper power setting and altitude to be used in design. Since the lowest CAT rises are available at the lowest pressure altitudes and the lowest power settings are most critical in regard for the need for heat, it is believed that the 50% normal rated power at 2000 ft. pressure altitude will provide the proper design conditions to meet requirements and provide an adequate installation. This will be further verified in the analysis of the energy balances in Chapter IV.

It should be noted that the data of Table III.1 does not include airspeed data since the photo observer was not operating. However, airspeed data are not necessary for developing equations since all temperatures were measured in the ducting including T_a at the inlet of the intake air duct which eliminates the kinetic energy temperature rise due to the airspeed of the aircraft and defined by $u^2/2gJc_p$. There is a kinetic energy temperature rise in the ducting, but this will be assumed negligible because of the generally low duct velocities. Hence, it is assumed that the total temperature T is equal to the indicated temperature T_{ind}. The validity of this assumption will be checked as follows:

A close approximation of the value of the total temperature T in an air-stream in terms of the indicated temperature T_{ind} and the velocity of the flow can be obtained from the following equations given in Reference 8:

$$r = .65 = \frac{T_{ind} - t}{T - t}$$

$$T = t + \frac{u^2}{2gJc_p}$$

combining we have

$$T - T_{ind} = .35 \frac{u^2}{2gJc_p}$$

From this it is shown that amount of error depends directly on the factor $.35u^2/2gJc_p$ or on the velocity of the flow u. Since it has been tentatively decided that the 50% N.R. sea level power is the proper design power, a check will be made of the velocity of induction air, interwarmer air and exhaust gas to determine extent of error. From Table IV.2, Chapter IV, it is shown that the induction system has a weight airflow of 1.632 lb/sec and the exhaust gas system a weight flow of 1.754 lb/sec. Using the flow equation $W = \rho ua$ or $u = W/\rho a$ we find that the induction air velocity is 48.9 ft/sec and the exhaust gas velocity is 64.5 ft/sec. It is also shown in Chapter IV that the interwarmer air velocity is 69.5 ft/sec and hence is greater than either the induction air flow or exhaust gas flows. Substituting this value in the above equation we have

$$T - T_{ind} = .35 \frac{u^2}{2gJc_p} = .35 \frac{(69.5)^2}{2x32.2x778x.24} = 1.41°R$$

Taking one of the highest temperatures in the interwarmer system $T_{2h} = 74°C$, 165.2°F, or 625.2°R for T_{ind} we have

$$T - T_{ind} = 1.41°R$$

626.61°R - 625.2°R = 1.41°R
or
166.61°F - 165.2°F = 1.41°F
or
74.8°C - 74°C = .8°C

Since the amount of error introduced .8°C is even less than the experimental error and that the recovery factor used in the above equation is conservative, the assumption that $T = T_{ind}$ is considered valid.

Analysis of the data of Table III.1 reveals that "Cold" temperature surveys will not be required in the establishment of energy balances for the interwarmer system. Further in order to facilitate thermodynamic use of this data the "Hot" temperature surveys have been reduced to degrees Rankine in Table III.2.

TABLE III.2
TEMPERATURE SURVEY

Pressure Altitude Ft	Nominal Power % MP	T_a	Induction System T_{1a}	T_{2a}	T_{3a}	T_{4a}	T_{5a}	T_{6a}	Interwarmer System T_g	T_{1g}	T_{1h}	T_{2h}	T_{3h}	T_{4h}
2000	100	501	501	511.8	510	542.4	537	538.8	1982	1964	616.2	616.2	592.8	546
	80	492	495.6	502.8	501	546	542.4	535.2	2038	2008	612.6	612.6	591.4	642.4
	65	492	493.6	501	501	555	536.8	549.6	2142	2104	634.2	637.8	546*3	551.4
	50	495.6	493.8	499.2	499.2	560.4	560.4	555	2059	2017	623.4	625.2	603.6	582.2
7500	100	501	502.8	535.2	537.0	569.4	569.4	569.4	2041	2023	641.4	643.2	616.2	569.4
	80	487.4	497.4	519.0	520.8	564	564	556.6	2041	2018	637.8	637.6	610.8	564
	65	493.8	495.6	515.4	517.2	573	573	567.6	2164	2127	654	659.4	628.8	574.8
	50	493.8	493.8	510.0	511.8	571.4	571.4	569.4	2087	2047	648.6	652.2	627	573
15000	100	483	483.0	558.6	562.2	573	573	574.8	2027	2012	645	645	610.8	573
	80	481.2	483.0	544.2	549.6	576.6	573.4	571.2	2041	2018	641.4	643.2	614.4	576.6
	65	475.8	475.8	533.4	538.8	573	571.2	565.8	2022	2002	639.5	641.4	614.4	573
	50	474	477.6	519.0	519.0	560.2	582	654	2096	2062	654.0	686.6	537.8	578.4
20000	100	*2												
	80	465	466.8	556.8	562.2	576.8	580.2	573	2064	2041	648.6	650.4	612.6	578.6
	65	465	466.6	555	556.8	580.2	580.2	573	2045	2023	646.8	652.2	619.8	580.2
	50	459.6	461.4	533.4	533.4	591.0	596.4	587.4	2094	2067	681.0	684.8	545	583.8
25000	100	*2												
	80	450.8	452.4	580.2	583.8	589.2	587.4	580.2	2064	2046	650.4	641.4	609	580.2
	65	445.2	447.0	569.4	569.4	574.8	571.2	573	2046	2025	634.2	636	601.8	569.4
	50	*2												

*Notes
1. All temperatures in °R, i.e. °F + 460°F
2. No data taken
3. Heat valve turned to cold position before survey was completed

CHAPTER IV - DEVELOPMENT OF EQUATIONS

General

In development of the design equations for the interwarmer induction air heating system it will be necessary to determine the energy balances for the various power settings and altitudes, developing the heat transfer equations for both the heat exchange at the interwarmer and at the exhaust manifold and finally setting up the empirical equations in terms of defined conditions. Prior to starting the development of equations, it is necessary to state certain fundamental concepts and assumptions. The process of the interwarmer system is assumed as steady one dimensional flow, constant pressure, with both media separated by metallic walls. It is also assumed that there is no heat loss through the duct walls to the surrouding atmosphere. This will be checked by the energy balance. Other assumptions regarding the heat exchange at the interwarmer and at the exhaust manifold are as follows:

a. Low pressure gas flows through the induction system, interwarmer system, and the exhaust manifold.

b. The flow in all components of the system is turbulent.

c. The heat transfer area is the same for both fluids.

d. Radiation between fluids and walls may be neglected.

e. Thermal resistance of the walls may be neglected.

f. Density of each fluid is constant.

g. Losses in head at the ends of the tubes may be neglected.

h. Potential and kinetic energy changes of airflow are considered negligible and no mechanical work occurs.

i. Difference between indicated temperature, T_{ind}, and total temperature T is negligible due to relatively low airflow and temperature.

Energy Balances

In order to set up the energy balance for both the induction system and the interwarmer system only the change in total enthalpy H need be considered. The energy balances are as follows:

Energy Balance for Induction System (1)

$$H_a + (H_{1a} - H_a) + (H_{2a} - H_{1a}) - (H_{2a} - H_{3a}) + (H_{4a} - H_{3a}) - (H_{4a} - H_{5a}) = H_{5a}$$

Intake Air	Ram Compression Rise	Turbo Rise	Loss to Interwarmer Entrance	Rise through Interwarmer	Loss to Carb. Top Deck	Carb. Top Deck

Energy Balance for Interwarmer System (2)

$$H_a + (H_{1h} - H_a) - (H_{1h} - H_{2h}) - (H_{2h} - H_{3h}) - (H_{3h} - H_{4h}) - (H_{4h} - H_a) = H_a$$

In-take Air	Rise over Exhaust Manifold	Loss to Control Valve Entrance	Loss to Inter-warmer Entrance	Loss over Interwarmer Tubes	Loss over-board	Outside Air

It should be noted that the weight air flows W_a and W_h are not required in equations (1) and (2) since they would cancel out. Expressing the above equations in terms of c_p and T since $H = c_pT$ we have

$$c_p\left[T_a + (T_{1a} - T_a) + (T_{2a} - T_{1a}) - (T_{2a} - T_{3a}) + (T_{4a} - T_{3a}) - (T_{4a} - T_{5a})\right] = c_pT_{5a} \text{ or}$$

$$T_a + (T_{1a} - T_a) + (T_{2a} - T_{1a}) + (T_{3a} - T_{2a}) + (T_{4a} - T_{3a}) + (T_{5a} - T_{4a}) = T_{5a} \quad (3)$$

$$c_p\left[T_a + (T_{1h} - T_a) - (T_{1h} - T_{2h}) - (T_{2h} - T_{3h}) - (T_{3h} - T_{4h}) - (T_{4h} - T_a)\right] = c_pT_a \text{ or}$$

$$(T_{1h} - T_a) + (T_{2h} - T_{1h}) + (T_{3h} - T_{2h}) + (T_{4h} - T_{3h}) + (T_a - T_{4h}) = 0 \quad (4)$$

It should be noted that c_p drops out of these equations, hence, the energy balances for both the induction system and interwarmer system may be checked out using only the total temperatures. Further, using the indicated temperature T_{ind} as total temperature, T will not (as shown in Chapter III) introduce any serious error due to relatively low airflows and temperature.

Also, all temperatures used would be T_{ind} and the relative difference between temperatures in the same medium would be the same.

Using equations (3) and (4) and the data of Table III.2, the changes in enthalpy for the various parts of the induction system and interwarmer system for the various altitudes and power setting at which tests were performed are shown in Table IV.1. A check of these energy balances reveals that all except two are in balance. One is out of balance by .2°R and the other by 10°R. These discrepancies are concentrated in the induction system energy balances, but are not believed to be of sufficient magnitude for concern. The causes for these discrepancies cannot be determined.

The interwarmer energy balance shows that the duct heat loss to the heat valve is negligible and that the heat loss at the valve to the inlet to the interwarmer tends to increase slightly with increasing power and altitude at pressure altitudes below 15,000 ft. This tendency is not apparent at higher altitudes probably due to the less dense air. It is believed that the loss at the valve is due primarily to its flexing since it is of cantilever construction. This loss could be minimized by a balanced type heat valve and hence, allow more heat for transfer to the induction air. However, even with this loss, sufficient heat is available. It should be noted that the greatest heat rise of the interwarmer air over the exhaust manifold and the greatest heat loss to the induction system over the interwarmer tubes occurs at the

TABLE IV.1

ENERGY BALANCES

Pressure Altitude Ft	Nominal Power %NR	Induction System							Interwarmer System						
		T_a	$T_{1a}-T_a$	$T_{2a}-T_{1a}$	$T_{3a}-T_{2a}$	$T_{4a}-T_{3a}$	$T_{5a}-T_{4a}$	T_{5a}	T_a	$T_{1h}-T_a$	$T_{2h}-T_{1h}$	$T_{3h}-T_{2h}$	$T_{4h}-T_{3h}$	T_a-T_{4h}	T_a
2000	100	501	0	10.8	1.8	32.4	-5.4	537	501	113.2	0	-23.4	-46.8	-45	501
	80	492	3.6	7.2	1.8	45	-3.6	542.4	492	120.6	0	-21.6	-48.6	-50.4	492
	65	492	1.6	7.2	0	54	1.8	556.8	492	142.2	3.6	-91.6*3	5.4	-59.4	492
	50	495.6	1.8	5.4	0	61.2	0	560.4	495.6	127.8	1.8	-21.6	-41.4	-66.6	495.6
7500	100	501	1.8	32.4	1.8	32.4	0	569.4	501	140.4	1.8	-27.0	-46.8	-68.4	501
	80	497.4	0	21.6	1.8	43.2	0	564	497.4	140.4	0	-27.0	-46.8	-66.6	457.4
	65	493.8	1.8	19.8	1.8	55.2	0	573	493.6	160.2	3.4	-30.6	-34.0	-81.0	493.6
	50	493.8	0	16.2	1.8	59.6	0	571.4	493.6	154.8	3.6	-25.2	-34.0	-79.2	493.8
15000	100	483	0	75.6	3.8	10.8	0	573	483	162	0	-34.2	-37.8	-90	483
	80	481.2	1.8	61.2	5.4	27.0	1.8	578.4	481.2	160.2	1.6	-28.8	-37.8	-95.4	481.2
	65	475.8	0	57.6	5.4	34.2	-1.8	571.2	457.8	163.8	1.8	-27.0	-41.4	-97.2	476.6
	50	474	3.6	41.4	0	61.2	1.8	582	474	180	12.6	-28.8	-39.4	-104.4	474
20000	100	*2													
	80	465	1.8	90.0	5.4	14.4	3.6	580.2	465	183.6	1.8	-37.8	-36	-111.6	465
	65	465	3.5	86.4	1.8	33.4	0	560.2	465	181.8	5.4	-32.4	-39.6	-115.2	465
	50	459.6	1.8	72.0	0	57.6	5.4	596.4	459.6	221.4	3.6	-39.6	-31.2	-124.2	459.6
25000	100	*2													
	80	450.6	1.8	127.8	3.8	5.2	-1.8	587.4	450.6	199.8	-9.0	-32.4	-28.8	-129.6	450.6
	65	445.2	1.8	122.4	0	5.4	-3.6	571.2	445.2	189.0	1.2	-34.2	-32.4	-124.2	445.2
	50	*2													

*Notes
1. All temperatures in °R, i.e., °F + 460°F
2. No data taken
3. Heat valve turned to cold position before survey was completed.
4. Minus (-) indicates heat loss; no sign indicates heat gain.

lower powers and at the higher altitudes. Comparison of the loss of heat over the interwarmer tubes to the heat gain through the interwarmer tubes into the induction air shows it approaches an equal exchange at the lower power settings, indicating the most efficient heat transfer conditions which would be expected. The interwarmer energy balance further shows a loss of heat overboard which is the greatest of all losses and which increases with decreasing power and increasing altitude. This is another source of heat loss which might be minimized by a different type heat exchanger, i.e., fin type or such type which would absorb the greatest possible amount of heat. This, however, is considered average and developing the equations assuming this type heat exchanger should be adequate.

Analysis of the energy balances for the induction system shows that the ram compression temperature rise, the duct heat loss to the interwarmer, and the loss from the interwarmer to the carburetor top deck are negligible. The induction air temperature rise through the turbo is shown to be the greatest at each altitude at the high power, decreasing with decrease in power and increasing with altitude. The induction air temperature rise through the interwarmer increases with decrease in power at all altitudes. It also indicates that the amount of rise decreases with increasing altitude, particularly at the higher power settings. This is due to the increasing induction air temperature rise through the turbo providing a small temperature difference between induction and interwarmer air, and resulting in a decreasing temperature rise through the interwarmer. For the purpose of design equations, the effect of the turbo should be neglected since it is negligible at 2000 ft. pressure altitude and since its effect cannot be included when designing to meet the established requirements.

The energy balances emphasize that the 2000 ft p.a. is the most critical, hence, designing for this altitude will provide more than adequate induction air temperature rise for any other flight altitude. It does not appear from these energy balances that designing for any one power at this altitude would be too critical and very similar results would probably be obtained, regardless of which was used. However, experience has shown that adequate induction air heating at low power and altitude conditions are the most important for extreme low temperature operation. These conditions are conducive to power instability in reciprocating engines caused by low cylinder head temperatures resulting in plug fouling from fuel condensation. Sufficient heat to meet this condition provides adequate heat to prevent or eliminate induction system icing. In view of the above and since the 50% normal rated power at 2000 ft. pressure altitude provides the best design conditions to meet requirements it will be used as the basis for design equations.

Heat Transfer Equations

In order to proceed further with design equations, it now becomes necessary to set up equations for the heat transfer at both the interwarmer and at the exhaust manifold. Since the process has been assumed as one dimensional steady flow, constant pressure, with both media separated by metallic walls, and no heat is lost through the duct walls to the atmosphere, we have rate of heat transfer at

Interwarmer

$$q = W_a (H_{4a} - H_{3a}) = W_h (H_{3h} - H_{4h}) \tag{5}$$

Exhaust Manifold

$$q = W_h (H_{1h} - H_a) = W_g (H_g - H_{1g}) \tag{6}$$

Note: The weight airflow of the exhaust gas is $W_g = W_a + W_f$ (7)

From equation (5) we have

$$\frac{W_h}{W_a} = \frac{(H_{4a} - H_{3a})}{(H_{3h} - H_{4h})} \tag{8}$$

and from equation (6) we have

$$\frac{W_h}{W_g} = \frac{(H_g - H_{1g})}{(H_{1h} - H_a)} \tag{9}$$

From equations (8) and (9)

$$W_h = \frac{W_a (H_{4a} - H_{3a})}{(H_{3h} - H_{4h})} = \frac{W_g (H_g - H_{1g})}{(H_{1h} - H_a)}$$

or

$$W_g = \frac{W_a (H_{4a} - H_{3a})}{(H_{3h} - H_{4h})} \times \frac{(H_{1h} - H_a)}{(H_g - H_{1g})} \tag{10}$$

Since $H = c_pT$, equations (8) and (9) become

$$\frac{W_h}{W_a} = \frac{c_{pa} (T_{4a} - T_{3a})}{c_{ph} (T_{3h} - T_{4h})} \tag{11}$$

$$\frac{W_h}{W_g} = \frac{c_{pg} (T_g - T_{1g})}{c_{ph} (T_{1h} - T_a)} \tag{12}$$

but $c_{pa} = c_{ph}$ since temperatures for both induction air and interwarmer air are near enough so as to cause a negligible error. It should be noted that $c_{pg} \neq c_{ph} = c_{pa}$ since the exhaust gas temperature is considerably higher. From Reference 6, $c_{pg} = .28$, if assumed equal to air in range of exhaust gas temperatures encountered, c_{ph} and c_{pa} will be considered $= .24$ for the range of temperature encountered. Entering these values, equations (11) and (12) become

$$\frac{W_h}{W_a} = \frac{(T_{4a} - T_{3a})}{(T_{3h} - T_{4h})} \tag{13}$$

$$\frac{W_h}{W_g} = \frac{.28\,(T_g - T_{1g})}{.24\,(T_{1h} - T_a)} = \frac{1.17\,(T_g - T_{1g})}{(T_{1h} - T_a)} \tag{14}$$

Reduction To Empirical Equations

In order to reduce the above to empirical equations, it is necessary to establish conditions of the heat exchange at both the interwarmer and at the exhaust manifold from conditions defined by test and requirements. Since it has been shown that the 50% normal rated power at 2000 ft. pressure altitude test data would provide an adequate system, these data will be used in setting up empirical design equations. As previously mentioned the original HIAD requirement described in paragraph b, Chapter III, is the most critical, and designing using this requirement will provide a system which will also meet the revision of this requirement. Accordingly, a system designed to provide a 36°C heat rise at 50% normal rated power at sea level with an OAT of -53.8°C should be more than adequate.

The energy balance for both the induction system and interwarmer system are (3) and (4), respectively

$$T_a + (T_{1a} - T_a) + (T_{2a} - T_{1a}) + (T_{3a} - T_{2a}) + (T_{4a} - T_{3a}) + (T_{5a} - T_{4a}) = T_{5a} \tag{3}$$

$$(T_{1h} - T_a) + (T_{2h} - T_{1h}) + (T_{3h} - T_{2h}) + (T_{4h} - T_{3h}) + (T_a - T_{4h}) = 0 \tag{4}$$

Since Table IV.1 and the previous discussion of the energy balance showed that the ram rise $(T_{1a} - T_a)$, turbo rise $(T_{2a} - T_{1a})$, heat loss to interwarmer $(T_{3a} - T_{2a})$, and loss to carburetor top deck $(T_{5a} - T_{4a})$ in the induction system are negligible for the 50% power at 2000 ft, equation (3) becomes:

$$T_a + (T_{4a} - T_{3a}) = T_{5a} \tag{15}$$

It was also shown that the heat loss to valve entrance $(T_{2h} - T_{1h})$ in the interwarmer system is negligible, hence, equation (4) becomes:

$$(T_{1h} - T_a) + (T_{3h} - T_{2h}) + (T_{4h} - T_{3h}) + (T_a - T_{4h}) = 0 \tag{16}$$

Enter the values for these various losses from the 50%, 2000 ft p.a. energy balance of Table IV.1 for the induction and interwarmer systems in equations (15) and (16) as applicable. The parts of equation (15) have values as follows:

$$T_a = T_a$$
$$(T_{4a} - T_{3a}) = 61.2°R$$
$$T_{5a} = T_{5a}$$

But $T_a = T_{3a}$ and $T_{4a} = T_{5a}$ since intermediate heat losses are considered negligible. Hence equation (15) becomes:

$$(T_{5a} - T_a) = 61.2°R \tag{17}$$

The parts of equation (16) have values as follows:

$$(T_{1h} - T_a) = 127.8°R \tag{18}$$

$$(T_{3h} - T_{2h}) = -21.6°R \tag{19}$$

but $T_{1h} = T_{2h}$, hence

$$(T_{3h} - T_{1h}) = -21.6°R \tag{20}$$

$$(T_{4h} - T_{3h}) = -41.4°R \tag{21}$$

$$(T_a - T_{4h}) = -66.6°R \tag{22}$$

Since airflow data available from tests conducted were inadequate and the induction system airflow determination is only adequate for checking purposes, it becomes necessary to make the best use of other available data. Data obtained from test stand operation in the Power Plant Laboratory, Directorate of Laboratories, WADC, with intake air 100°F (37.8°C) and exhaust temperature of between 1600°F to 1700°F (870°C to 926°C) together with the flight test nominal power, rpm, and mp for which it will be used is shown in Table IV.2. For comparative purposes the induction system mass air flow will be determined using the metering suction differential (MSD) at 2000 ft on page 4, Appendix III, Reference 9, 2200 RPM (80% N.R.), 2100 RPM (65% N.R.), and 1700 RPM (50% N.R.); reading the airflow from the chart on page 3, Appendix II, Reference 9, and computing the airflow as described in Appendix II, Reference 9. Mean Suction Differentials (MSD) thus obtained and converted to In H_2O, namely 17.85, 14.92 and 7.62, provide induction system airflows of 2.78, 2.50 and 1.74 lb/sec. These airflows compare fairly well with corresponding induction system airflows W_a of Table IV.2. The best agreement is shown at the 50% N.R. power which is the power setting selected for design.

It is believed that the selection of the test stand data for the flight power settings is a valid approximation since (1) there is very little difference in the density of the air between the test stand and flight test data even if the latter is unsupercharged, (2) the variations in rpm and mp balance each other, (3) the check of induction system airflow from flight test data mentioned above shows favorable agreement, and (4) accuracy is within that of investigation. Using the airflow data of Table IV.2, the temperature data of Table III.2 at the 2000 ft p.a., equations (13), (14), and $W_g = W_a + W_f$, the interwarmer air weight flow, W_h, has been computed for each power setting. Although airflow data were taken at a p.a. of 819 ft. and temperature data at 2000 ft p.a., all development of equations will be considered for sea level conditions since design requirements are thus specified. This procedure is also considered within the accuracy of the investigation. The resulting interwarmer air weight flow from each of these equations is given in Table IV.3.

Obviously the W_h computed from equation (14) is inadequate. This may be caused by the fact that the heat rise over the exhaust manifold may be due to other heat besides that indicated by the change in enthalpy over the

TABLE IV.2

INDUCTION AIR, FUEL, AND EXHAUST GAS WEIGHT FLOWS FOR R3350 ENGINE

Nominal Power % N. R.	Flight Test 2000'		Test* Stand		Induction Air Flow W_a		Fuel Flow W_f		Ex Gas Flow W_g
	rpm	mp	rpm	mp	lb/hr	lb/sec	lb/hr	lb/sec	lb/sec
100	2400	41.8	2400	44	13850	3.85	1385	.385	4.235
80	2200	35.0	2211	32.3	8850	2.46	820	.226	2.688
65	2100	32.8	2015	33.2	8350	2.32	445	.124	2.444
50	1700	30.8	1360	35.0	5880	1.63	439	.122	1.754

*Test stand data taken at local altitude at WPAFB, i.e. 819 ft.

TABLE IV.3

COMPARISON OF COMPUTED INTERWARMER AIR WEIGHT FLOWS

Nominal Power % N.R.	W_h from Equation (13) lb/sec	W_h from Equation (14) lb/sec
100	2.67	.772
80	2.28	.781
65	2.78	.765
50	2.414	.675

section of the exhaust manifold from the firewall to the turbo. Some heat may be picked off from the turbo and some may be sucked in from the engine section. However, much of this discrepancy may also be due to the use of only one thermocouple in the middle of the duct, which would not indicate an enthalpy loss in the exhaust gas nearer the inside surface of the exhaust gas manifold. These undefined sources of error must be considered as a constant and would be only applicable under similar conditions of installation and instrumentation. Hence equation (14) becomes:

$$W_h = \frac{1.17\ K\ W_g\ (T_g - T_{1g})}{(T_{1h} - T_a)} \tag{23}$$

where $K = \frac{2.414}{.675} = 3.56$ at 50% N.R. power, hence

$$W_h = \frac{4.18\ W_g\ (T_g - T_{1g})}{(T_{1h} - T_a)} \tag{24}$$

It now becomes necessary to determine an expression of the minimum area of the ducting in the interwarmer system to produce a desired carburetor air temperature rise in terms of the induction air weight flow. Using the basic flow equation

$$W_h = \rho u A$$
$$u = \frac{W_h}{\rho A} \tag{25}$$

where

W_h = 2.414 lb/sec from Table IV.3 at 50% N.R. power
ρ = .07651 lb/ft^3
A = Elbows 39.4 in^2 AF part No 48J20924
26.0 in^2 AF part No 48J20923
65.4 in^2 or .454 ft^2

Intercooler Exit Shutter Boeing Part No. 14-2326-1 has dimensions of 1.75" x 26" when opened to end of green range = 45.5 in^2 or .316 ft^2

The areas given above are minimum in the interwarmer ducting. The elbow areas are believed the best for design use since there is a velocity increase at the intercooler or interwarmer exit due to the venturi effect of the slipstream which tends to decrease the opening required to maintain uniform flow.

Therefore

$$u = \frac{2.414}{.07651 \times .454}$$

= 69.5 ft/sec. is the velocity of flow in the interwarmer system for the best performance.

From equation (25) we have

$$A = \frac{W_h}{\rho u} = \frac{W_h}{.07651 x 69.5} = .188\ W_h \tag{26}$$

Equation (26) is an expression of the minimum area of the interwarmer ducting. The exit area of the venturi flap is shown from above to require only 70% of this area to maintain the same flow.

In order to obtain empirical equations for the rate of heat transfer we must introduce the empirical relationships in equations (5) and (6). Hence we have at interwarmer

$$q_i = W_a c_{pa}(T_{4a} - T_{3a}) = W_h c_{ph}(T_{3h} - T_{4h}) \tag{27}$$

$$= W_a .24(61.2) = W_h .24\ (41.4)$$

$$= 14.7\ W_a = 9.94\ W_h \tag{28}$$

and at the exhaust manifold

$$q_{em} = W_h c_{ph}(T_{1h} - T_a) = 4.18\ W_g c_{pg}(T_g - T_{1g}) \tag{29}$$

$$= W_h x .24 x (127.8) = W_g x 4.18 x .28(42)$$

$$= 30.7\ W_h = 48.2\ W_g \tag{30}$$

Dividing the rate of heat transfer by the corresponding weight flow gives the quantity of heat transferred at each heat exchange. Hence at interwarmer the heat gained by the induction air is

$$Q_{ia} = \frac{q_i}{W_a} = 14.7\ \text{BTU/lb} \tag{31}$$

and the heat lost by the interwarmer air is

$$Q_{ih} = \frac{q_i}{W_h} = 9.94\ \text{BTU/lb} \tag{32}$$

At the exhaust manifold the heat gained by the interwarmer air is

$$Q_{emh} = \frac{q_{em}}{W_h} = 30.7\ \text{BTU/lb} \tag{33}$$

and the heat lost by the exhaust gas is

$$Q_{emg} = \frac{q_{em}}{W_g} = 48.2\ \text{BTU/lb} \tag{34}$$

In summation, sufficient equations have been provided to (1) set up induction and interwarmer system energy balances for a proposed system, (2) compute required interwarmer flow from both the induction system air weight and exhaust system gas weight flow equations, (3) determine minimum duct area for the interwarmer system, and (4) determine rate of heat transfer and quantity of heat transferred at each heat exchange. A design using these equations will be developed for the Pratt & Whitney R4360-53 engine in the next chapter.

CHAPTER V - APPLICATION TO DESIGN

General

In order to illustrate the application of the design equations developed in the preceding chapter, an interwarmer system will be designed for an R-4360-53 engine on a B-36 type aircraft. Air, fuel, and exhaust gas weight flow test stand data obtained from the Pratt & Whitney Engine Unit, Power Plant Laboratory, which will be used in this design problem is shown in Table V.1. The basic assumptions which applied in the development of the design equations will also be considered applicable to this problem. Further, it will be assumed that the induction and interwarmer system is similar to that of the B-29, ie., containing intercooler-interwarmer, turbosupercharger, heat control valve, exit intercooler shutter, exhaust manifold heat source for interwarmer system, the efficiencies of the heat exchanges at both the intercooler and at the exhaust manifold are approximately the same as those on the B-29, and heat losses are similar. These assumptions are valid since turbosupercharged engine installations are very similar. The following factors will apply to the design of this system:

a. The heat source will be the exhaust manifolds.

b. Flow of hot air over intercooler tubes is induced by the venturi effect over an open exit intercooler shutter.

c. A heat valve such as the balanced type which would provide minimum leakage of cold air when valve is in the hot position is utilized.

d. Fire valves in the interwarmer system ducting near the hot air intake from around the exhaust manifolds are provided.

e. Ducting is designed keeping area changes and reversals of flow to a minimum.

f. Valve installation is designed so that flow of cooling air is not restricted when the heat valve is in the cold position.

g. Heat control valve is designed for only hot and cold positions.

h. Control of the intercooler exit shutter is sufficiently accurate to meet HIAD requirements which will allow selective and accurate control of induction air temperatures.

i. Induction air temperature is measured at carburetor top deck.

In accomplishing this design it will be necessary to set energy balances using the OAT and heat rise specified in the requirements paragraph b, Chapter III, then heat transfer conditions will be established, the interwarmer air weight flow W_h computed using W_a and W_g from above, and the area of the ducting computed from the interwarmer air weight flow W_h.

TABLE V.1

INDUCTION AIR, FUEL, AND EXHAUST
GAS WEIGHT FLOWS FOR R-4360-53 ENGINE

Power				Induction Air Flow W_a		Fuel Flow W_f		Exhaust Gas Flow W_g	
%N.R.	BHP	RPM	MP	lb/hr	lb/sec	lb/hr	lb/sec	lb/hr	lb/sec
100	2880	2600	51	19600	5.45	1900	.53	21500	5.98
70.1	2020	2300	44	15000	4.17	905	.25	15905	4.42
61	1760	2000	41.8	13800	3.83	714	.1983	14514	4.03
55	1380	1800	39.5	11900	3.31	625	.1735	12525	3.48
42.4	1220	1550	34.0	9000	2.5	500	.139	9500	2.64

Notes: 1. Altitude at WPAFB, i.e. 819'
2. CAT = 68°F, OAT = 35°F to 50°F

Energy Balances

The energy balance for the induction system was reduced to equation (15) which is

$$T_a + (T_{4a} - T_{3a}) = T_{5a}$$

From the requirement of paragraph b of Chapter III, we note that

$$T_a = -53.8°C, -65°F \text{ or } 395°R$$

and from equation (17)

$$T_{5a} - T_a = 61.2°R$$

therefore $T_{1a} = 395°R$, $T_{2a} = 395°R$, $T_{3a} = 395°R$, $T_{4a} = 456.2°R$, and $T_{5a} = 456.2°R$.

The energy balance for the interwarmer system was reduced to equation (16) which is

$$(T_{1h} - T_a) + (T_{3h} - T_{2h}) + (T_{4h} - T_{3h}) + (T_a - T_{4h}) = 0$$

Equations (18) through (22) provide values for these enthalpy changes so that when $T_a = 395°R$, $T_{1h} = 522.8°R$, $T_{2h} = 522.8°R$, $T_{3h} = 501.2°R$ and $T_{4h} = 459.8°R$.

The above establishes the temperatures throughout both the induction and interwarmer systems. For the exhaust system the temperatures $T_g = 2059°R$ and $T_{1g} = 2017°R$ should be used as these were the temperatures from the B-29 installation and should be valid.

Heat Transfers

It is now possible to determine the interwarmer system mass airflow W_h from the induction system flow W_a and exhaust gas flow W_g of Table V.1 at 55% Normal Rated Sea Level Power. It was decided to determine interwarmer weight airflow, minimum duct areas, and rate of heat transfer for the 55% N.R. power since no 50% N.R. power data were available. This is on the conservative side since a greater weight airflow will provide a greater duct area.

From equation (13) we have

$$W_h = \frac{W_a (T_{4a} - T_{3a})}{(T_{3h} - T_{4h})} = \frac{3.31 \times 61.2}{41.4} = 4.9 \text{ lb/sec}$$

From equation (24) we have

$$W_h = \frac{4.18\, W_g (T_g - T_{1g})}{(T_{1h} - T_a)} = \frac{4.18 \times 3.48 \times 42}{127.8} = 4.78 \text{ lb/sec}$$

It is shown that W_h computed from either equation (13) or (24) provides very close agreement, hence, $W_h = 4.9$ lb/sec will be used in subsequent computations.

Assuming that the best velocity of flow would be 69.5 ft/sec as in the B-29 system we can obtain the minimum area of the duct from equation (26) which is

$$A = .188\ W_h = .188 \times 4.9 = .921\ \text{ft.}^2$$

Knowing the minimum duct area the ducting for the system may be designed.

The exit area of the intercooler shutter was shown to be 70% of the minimum area, hence, for the B-36 this would yield an area of $.644\ \text{ft}^2$. The intercooler exit shutter indicator would then be marked to indicate this maximum position by opening the shutter sufficiently to provide that area.

The rate of heat transfer per unit time at both the intercooler and exhaust manifold may be obtained from equations (28) and (30).

Therefore at interwarmer

$$\begin{aligned} q_i &= 14.7\ W_a = 9.94\ W_h \\ &= 14.7 \times 3.31 = 9.94 \times 4.9 \\ &= 48.6\ \text{BTU/sec} = 48.6\ \text{BTU/sec} \end{aligned}$$

and at exhaust manifold

$$\begin{aligned} q_{em} &= 30.7\ W_h = 48.2\ W_g \\ &= 30.7 \times 4.9 = 48.2 \times 3.48 \\ &= 150.5\ \text{BTU/sec} \approx 168\ \text{BTU/sec} \end{aligned}$$

The rate of heat transfer at the interwarmer, q_i, shows very good agreement computed from both W_a and W_h. The computation at the exhaust manifold q_{em} however does not show as favorable results when computed using both W_h and W_g but is believed that an average of the two values would be sufficiently accurate. Hence, rate of heat transfer at the interwarmer into the induction air is

$$q_i = 48.6\ \text{BTU/sec}$$

and the rate of heat transfer at the exhaust manifold from the exhaust gas to the interwarmer air is

$$q_{em} = 159.3\ \text{BTU/sec}$$

The quantity of heat transferred at the interwarmer and at the exhaust manifold is given by equations (31), (32), (33), and (34) without any further computation.

From the determinations made above, the conditions around the heat exchange at both the intercooler or interwarmer and at the exhaust manifold are known. From these conditions, it is possible to check the adequacy of the intercooler as an interwarmer, or to design a new heat exchanger. Further, the defined conditions at the exhaust manifold will permit design of a heat exchanger, or enable drawing warm air from a sufficient length of the exhaust manifold to provide adequate heating of interwarmer air.

The above represents the extent to which design will be accomplished. It was not the purpose of this report to go into detail design, but rather to provide sufficient equations and information so that detail design could be made for specific applications.

CHAPTER VI - SUMMATION AND CONCLUSION

In the preceding chapters the factors leading to the design of the Interwarmer Induction Air Heating System, the description of the system and instrumentation used to obtain design data, and test procedures were discussed. Empirical equations were developed using a combination of flight test and test stand data because of circumstances beyond the control of the author. Temperature surveys were obtained from flight tests and induction air, fuel, and exhaust gas weight flow from test stands. While it was realized that this was not the ideal procedure, it was the only alternative since further testing was not considered warranted. It is believed that this approach will be adequate and will provide satisfactory results. The equations thus developed were used to define conditions for design of an interwarmer system for the R-4360-15 Pratt and Whitney engine in a B-36 aircraft. Detail design was not accomplished since such was considered beyond the scope of this report.

In applying the interwarmer system to any type of reciprocating engine installation, it is only necessary to obtain the induction air weight flow, and fuel weight flow for the engine to be provided with the system. Next consider all the design factors listed in the previous chapter and prepare a preliminary drawing of the interwarmer, induction, and exhaust systems introducing temperature and airflow symbols in accordance with Figure II.8. Set up the energy balance equations (15) and (16) for both the induction and interwarmer systems using $T_a = -53.8°C$ ($-65°F$) and $T_{5a} = -17.8°C$ ($0°F$) modifying as necessary so as to accurately reflect energy balances of both the induction system and interwarmer system. For instance, it may be decided that a valve installation such as a balanced type would have only half the leakage, hence, only half the heat loss of the cantilever type. Hence, this savings should be distributed throughout both the induction and interwarmer system energy balances as required. These energy balances then define the temperatures throughout both the interwarmer and induction systems. Listing each temperature, in lieu of temperature differences, then defines the conditions for the heat exchanges into the induction air at the interwarmer and from the exhaust gas at the exhaust manifold from which the interwarmer air weight flow W_h may be computed from equations (13) and (24). Knowing the air and gas weight flows and enthalpy changes over both the induction and exhaust system heat exchanges, the BTU/sec or BTU/lb which must be transferred from the exhaust gas to the interwarmer air to the induction system air can be determined from equations (28), (30), (31), (32), (33), and (34) and suitable heat exchangers designed.

It should be noted that turbosupercharged aircraft engines lend themselves to this design since an intercooler to serve as an interwarmer already exists in the induction system. However, it is believed that application to low power non-turbosupercharged engines could be advantageously accomplished. A very simple heat exchanger could be designed and installed in the induction system. The heat control valve could be operated by a push-pull type flexible control rather than by an electro-mechanical actuator. The exit shutter, or regulating valve, could also be operated by a flexible push-pull type rod, or the cowling could be raised and a fixed opening provided to induce hot airflow from a non-ram source over the heat exchanger in the induction system. This latter method would be preferred, and the heat control valve would then be used as a regulator to select and maintain a fixed intake air temperature. A cold air source is not necessary for a non-turbosupercharged aircraft engine since no heat of compression would have to be dissipated.

In conclusion, it is desired to emphasize that the interwarmer design, although originally designed for turbosupercharged aircraft engines, will provide an effective intake air conditioning system for non-turbosupercharged aircraft engines. It is believed that its greatest potential lies in the field of low power reciprocating engines and the improved performance which would result from such application would warrant the effort expended.

APPENDIX

Nomenclature

Symbol	Description	Units
A	area cross-sectional	sq. ft.
c_p	specific heat at constant pressure	BTU/lb°R
g	acceleration of gravity	32.2 ft/sec^2
H	total enthalpy	BTU/lb
J	mechanical equivalent of heat	778 ft lb/BTU
K	constant	dimensionless
p	static pressure	lbs/ft^2
P	total pressure	lbs/ft^2
q	heat rate or quantity of heat per unit time	BTU/sec
Q	quantity of heat	BTU/lb
r	recovery factor	dimensionless
t	static temperature	as indicated
T	total temperature	as indicated
T_{ind}	indicated temperature	as indicated
u	velocity	ft/sec
W	weight flow	lb/sec
ρ	density	lbs/ft^3

Subscripts

a	free air or induction system inlet
1a	induction system air turbo inlet
2a	induction system air turbo outlet
3a	induction system air interwarmer inlet

4a	induction system air interwarmer exit
5a	induction system air carburetor top deck
6a	induction system air carburetor bottom deck
g	exhaust gas near firewall
1g	exhaust gas near turbosupercharger
1h	interwarmer system air outlet side of exhaust manifold heat exchanger
2h	interwarmer system air heat valve inlet
3h	interwarmer system air heat valve outlet and inlet to interwarmer
4h	interwarmer system air interwarmer outlet
f	fuel
em	exhaust manifold
emg	exhaust gas at exhaust manifold
emh	interwarmer air at exhaust manifold
i	intercooler or interwarmer
ia	induction air at interwarmer
ih	interwarmer air at interwarmer

Abbreviations

Item	Description
CAT	carburetor air temperature
carburetor	This term used in lieu of terminology air regulator, or master control, which takes place of carburetor on fuel injection engines to simplify expression and eliminate confusion.
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
in	inch (es)

Item	Description
in^2	square inch (es)
lb	pound (s)

References

1. Air Technical Service Command Memorandum Report, Serial Number TSESE-4-42, "Carburetor Heat for Turbosupercharged Engines," dated 19 May 1945, by Edward C Theiss.

2. Air Materiel Command Memorandum Report, Serial Number MCREOC-48-12, "Interwarmer Type Carburetor Heat System for Turbosupercharged Engines," dated 16 August 1948, by Edward C Theiss.

3. Air Materiel Command Memorandum Report, Serial Number MCREOC-48-13, "Recirculating Type Carburetor Heat System for Turbosupercharged Engines," dated 14 October 1948, by Edward C Theiss.

4. Air Materiel Command Memorandum Report, Serial Number MCREOC-50-4, "Balanced Type Heat Valve for Interwarmer Type Carburetor Heat System," dated 3 February 1950, by Edward C Theiss.

5. Air Materiel Command Memorandum Report MCREOC-50-6, "Fire Valve for the Interwarmer Induction Air Heating System," dated 12 July 1950, by Edward C Theiss.

6. "Thermodynamic Properties of Air" by Joseph H Keenan and Joseph Kaye, John Wiley and Sons, Inc, 1945.

7. "Introduction to Heat Transfer" by Brown and Marco, First Edition, New York and London, McGraw-Hill Book Company, Inc, 1942.

8. "Thermodynamics of Compressible Fluid Flow (class notes for ME 801)" by Richard H Zimmerman, Department of Mechanical Engineering, The Ohio State University, Columbus, Ohio, Fall Quarter 1951.

9. WADC Memorandum Report, Serial Number WCT-52-22, "Interwarmer Induction Air Heating System, Exhaust Manifold Temperature Survey and Airflow Determination," dated 20 June 1952, by Lt Edward A Fox.